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Solar-terrestrial relations : flare and solar wind effects

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Abstract

The existence of Solar Terrestrial Relations is clearly shown during solar flare events. During these catastrophic events the enhanced flux of XUV solar radiation as well as the sudden outburst of energetic solar cosmic ray particles induce a series of well identified effects in the Earth's magnetic field, in the terrestrial ionosphere and in the upper atmosphere. These geophysical effects and their solar origin will be reviewed in the first part of this article.

Solar activity also perturbs the distribution of plasma and magnetic fields in the corona and in the interplanetary medium. It produces large-scale (low frequency) and small-scale (high frequency) inhomogeneities (perturbations) are produced in the expanding solar wind flow which then interacts with the Earth's magnetic field. The resulting variability of the impinging solar wind plasma triggers additional geophysical effects in the magnetosphere, in the terrestrial ionosphere and in the upper atmosphere. Some of the geophysical consequences of this non-stationary interaction of the solar wind with the geomagnetic field, and, of impulsive penetration of small scale solar wind plasma irregularities into the magnetosphere will be reviewed in the second part of this article (e.g. polar cusp fields, currents, and related ionospheric irregularities).

1. Introduction

First evidence that the Sun is not a changeless, immutable light and heat source, came very early from the observations of changing spots on the Sun's surface. These sunspots appear to develop at unforeseable places, and they disappear after a lifetime varying between two and a hundred days. The number of sunspots is variable over a period roughly equal to two times eleven years : the period of the solar activity cycle. (see fig. 1).

That the Sun is changing and can become suddenly very active over periods of minutes, was discovered in 1859 by R.C. Carrington and R. Hodgson when they observed for the first time what is now known as a "solar flare" ; they described what they observed in the midst of a large sunspot group, as "two patches of intensely bright and white light which suddenly break out".

2. Solar Flares

Flares are the most dramatic eruptions which release over their short lifetime (5 to 100 minutes) a total energy ranging between 10^{28} ergs (in the case of subflares) and 10^{32} ergs (in the case of a Flare of class 4. Even relatively frequent small flares expend an amount of energy equivalent to millions of hydrogen bombs.

The rate of occurence per day (E) of solar eruptions varies in phase with the relative sunspot number (R ; also called Wolf number) :

$$E = 0.04\, R[d^{-1}] \text{ (Ref.1).}$$

One of the most studied superflares is that of November 12, 1960. Most recently a series of six large flares was observed during the period of 3-7 February 1986. This series of events triggered a very intense geomagnetic storm and caused disruptions in electric power lines (Refs. 8, 9).

A) Origin of flares and electromagnetic radiation

The origin of solar flares remains an unresolved physical problem ; however, since magnetic field intensities are always high (10^{-2} to 1 Tesla) in solar flare areas, magnetohydrodynamists generally speculate that these explosions result from the conversion of magnetic energy into kinetic energy. This should, in principle, occur along neutral lines or at neutral points where the magnetic field intensity reverses direction : magnetic field lines are assumed to reconnect (or to merge) at these places ; this is supposed to give explosive flare events. Most of these Reconnection models, however, are steady state or quasi-steady ; induced (A.C.) electric fields are ignored in "stationary" MHD models for these highly (non-stationary) explosive events! Therefore one can but wonder what is the actual relevance of current reconnection models in the case of highly non-stationary hydrodynamical solar flare events. But other physical mechanisms should not be excluded to explain the origin of solar flares.

It is known that the explosion of energy takes place in the chromosphere and the low altitude region of the corona where the temperature increases from the minimum photospheric value (4400 K) to more than a million degrees in the solar corona over an altitude range of less than 0.02 R_S (R_S is the solar radius : 6.9 x 10^8 m).

The gigantic energy release is exported by a brilliant burst of visible light (H-alpha) and of electromagnetic waves ranging from X-rays to radio waves, by ions and electrons accelerated to more than half the speed of light, and, by clouds of ionized gas that sweep through interplanetary space at 700-800 km/s. Recently, the study of high-energy flares has been greatly advanced by spacecraft observation of gamma-ray spectra and neutron fluxes (Ref. 25).

The solar X-ray, like the solar radio emissions, originate from both thermal and non-thermal processes that take place primarily in the solar corona. Non-thermal X-ray emissions occur mainly at short wavelengths less than about 0.5 nm corresponding to photon energies greater than 2 keV (Ref. 7, 36). Gamma ray line observations of fluxes from SMM and Hinotori satellites do not support the two phase concept of solar flare development.

B) **Geophysical effects of electromagnetic radiation of solar flares**

Among the most spectacular geophysical effects produced by bursts of hard X-rays are Sudden Ionospheric Disturbances (SID). These ionospheric disturbances are observed in the sunlit hemisphere and arise simultaneously with visual flare observation H-alpha. The geophysical effects result from the enhanced ionization of the E- and D-regions of the terrestrial ionosphere (Ref. 36). SIDs and the subsequent recovery of the ionosphere have a time duration somewhat longer than the flare duration ; generally from a few minutes to an hour, with more rapid rise than decay.

Several SID observations are routinely identified and digitized. Let us just mention a few of the most important of them

1) Solar Flare Effects (SFE), or Crochets, are observed as a small hook on magnetometer records. They are caused by the magnetic field response to increased current flow in the E-region due to electron density enhancement induced by flare X-rays.

2) Short Wave Fadeouts (SWF), are observed from signal strength records of shortwave receivers (3 to 30 MHz). Signals from sweep-frequency ionosondes may be completely absorbed as a consequence of the enhancement of electron density induced by solar flare X-rays in the D-region.

3) When an SID occurs, the vertical height of reflection is suddenly lowered, and the path length shortens. Ionospheric disturbances resulting in this changed path length are known as Sudden Phase Anomalies (SPA).

4) Sudden Enhancement of Atmospherics (SEA), are observed as an increase in signal strength on wideband equipment operated to detect electromagnetic emissions from lightning at frequencies ranging between 10 and 50 kHz

There are also other types of SID's and geophysical effects produced by the bursts of electromagnetic radiation emitted by the Sun at the onset of flares. A comprehensive list of these effects is given for example in the Handbook of Correlative Data (Ref.2).

C) **Corpuscular radiations emitted by flares and their geophysical effects**

1) Solar Energetic Particles (SEP)

Significant fluxes of electrons, protons and multiply charged ions are accelerated at the Sun during energetic solar flares. Some of these MeV particles are subsequently detected within the interplanetary medium and in the Earth magnetosphere.

The largest flares release protons and heavy ions with energies up to 10 GeV i.e. overlapping in energy with the galactic cosmic rays (see fig. 2). The heavy metallic ions with low first ionization potentials have been found to be relatively more abundant in the streams of Solar Energetic Particles, compared to their abundances in the photosphere (Ref. 3).

The penetration of these energetic particles in the Earth's atmosphere is easiest at higher latitudes. Meeting weaker resistance from the geomagnetic field over the polar caps these protons crash into the atmosphere, exploding the molecules of Oxygen and Nitrogen that they hit into many energetic shower particles which reach the ground over a wide area.

The penetration of Solar Energetic Particles (SEP) into the polar cap ionosphere enhances considerably the ionization in the D-region. Consequently Solar Proton Events (SPE) are marked by strong radio absorption which is observed 15 to 100 minutes after the visual flare brightening. These absorption eventswhich are called Polar Cap Absorptions (PCA), may persist for 1 to 6 days.

By timing the arrival of particles of different speeds, satellite measurements have shown that while all the particles have been produced simultaneously in the flare and have travelled the same distance, the distance covered is generally much larger than that from the Sun to the Earth ; this suggests a roundabout trajectory resulting from numerous "collisions" of the particles with irregularities in the spiral interplanetary field (pitch angle scattering).

Both the intensity and spectrum of solar cosmic protons and heavy ions depend on the relative position of the Earth and the flare on the Sun. The actual amount of particles bombarding the magnetosphere and the atmosphere of the Earth depends therefore on the interplanetary conditions at the time of the flare. These conditions are, however, highly variable and unpredictable. This effect may lead to a variation by factors as large as 100 in the observed flux, at different points around the orbit of Earth from the same flare (Ref. 6).

2) Interplanetary shock waves

Solar energetic particles can reach the Magnetosphere of the Earth in less than one hour, but they do not contribute much to the thermal plasma density forming the bulk of the solar corona and solar wind. Within one or two days after a burst of SEP, particles from the solar plasma begin to arrive at the edge of the geo-magnetosphere i.e. at the magnetopause. The solar wind bulk velocity is then enhanced from less than 400 km/s (prevaling during quiet solar wind conditions and in interstream regions) up to 700-800 km/sec in the post- shock plasma ejected out of the corona after large solar flares.

When such a shock front hits the magnetopause the dayside region of the magnetosphere is "compressed". The sudden impulse (s.i.) or the storm sudden commencement (ssc) observed in magnetograms are the manifestation at ground level of this magnetospheric compression due to the enhanced solar wind pressure (see fig.3).

When the interplanetary magnetic field is directed southward at the time of this interaction the magnetic perturbation is likely to develop into a geomagnetic storm with a main phase and a recovery phase lasting for several hours and sometimes longer than a day.

During the storm sudden commencement phase, the mid and low latitude values of H (the horizontal component of the geomagnetic field) are simultaneously increased worldwide, typically by a few tens of nanoteslas (gammas). This state of enhanced H may persist for a few tens of minutes during the initial phase. During the following main phase of the magnetic storm, H is depressed below its prestorm value typically by several tens to a few hundred nanoteslas for many hours. The recovery phase, or return to prestorm state, usually requires a few days. These two latter phases are due to the great enhancement and gradual decay of a large scale diamagnetic ring current set up within the magnetosphere.

Because of their relatively low energy (~ keV) the solar wind protons enter preferentially into the magnetosphere and down into the earth's atmosphere along high latitude magnetic field lines. The easiest and most direct access for solar wind particles is via the polar cusps which are formed by all magnetic field lines parallel to the magnetopause or traversing it (see fig.4) (Refs.4,5).

The whole polar caps are also invaded by the thermal solar wind proton forming there what has been called the Polar Rain (Ref.34). The polarity of the interplanetary magnetic field controls very effectively the access to the Northern and Southern polar caps (Ref.37).

3. Solar wind and its interaction with the Earth

Besides geophysical effects triggered from time to time by emissions of solar flare radiation and corpuscules, as recalled in the previous section, there is a whole class of solar terrestrial relationships linked to the existence of the solar wind interacting with the Earth's magnetic field, even in absence of flare events. Indeed, geomagnetic storms are often triggered by collisionless shocks which are not related to solar flare events, but which are caused by disappearing filaments, coronal holes (Refs. 9,29) or other unknown or yet unclear causes. Furthermore, as a consequence of their unfavorable location on the solar disk, some flares do not produce significant effects at the Earth.

A. Origin and models of the solar wind

The existence and origin of the solar wind can be explained from different alternative points of view. In Appendix 1 we have followed the approach of kinetic theory which shows more explicitely and directly than any fluid approach why protons are accelerated out of the solar gravitational potential and why they obtain supersonic velocities at large heliocentric distances.

It is now well established that in the solar wind, there are two flow regimes : (i) high speed streams separated by regions where the bulk velocity is smaller than 400 Km/s, and, where the density is comparatively large ; (ii) the interstream slow solar wind which is mainly observed at boundaries of magnetic sectors and in vicinity of magnetic neutral sheets.

High speed streams are observed on both sides of interplanetary current sheets and IMF sector boundaries. They originate in regions of the solar corona where the plasma density and temperature are significantly depressed, and, where the magnetic field lines are "open", i.e. extend from the Sun far out beyond the orbit of the Earth ; these low temperature regions appear darker in X-Ray images of the corona and are called coronal holes.

Among the many surprising features observed in fast streams is the unexpected presence of narrow field aligned beams of suprathermal electrons which have been called "strahl electrons" (Ref. 19). These "strahl electrons" form a peculiar subpopulation besides the "core" and "halo" electrons which are observed in slow solar wind regimes (Ref.39). The origin of "strahl electrons" is still unknown !

The heavy ion abundances and temperatures also differ significantly in the two flow solar wind regimes (Ref.40). Many of these peculiarities remain unexplained and cannot be accounted for by current hydrodynamical models unless some ad hoc assumption is invoked to make them work and fit the observations. Ad hoc intensities of MHD waves and their expected dissipation in the Chromosphere and Corona up to 10 R_S, is the 'Deus ex machina' usually invoked !

B. Interaction of the solar wind and magnetosphere

Most large-scale solar wind models are based on simplifying assumptions such as : (i) stationary flow and (ii) the absence of small scale plasma irregularities i.e. near uniformity of the plasma. Dozens of models for slow solar wind and high speed streams are based on these two easy and convenient assumptions. For more than two decades this has lead other theoreticians to consider that the interaction between the solar wind and the geomagnetic field could satisfactorily be described as a stationary or quasi-steady-state interaction. Tens of magnetospheric models produced since 1960 are indeed based on these easy and convenient assumptions i.e. (i) stationary flow and (ii) uniformity of the flow impinging on the magnetopause surface.

The deflection of a stationary laminar solar wind flow around the terrestrial magnetic obstacle can to some extent be simulated in the Laboratory ; when a neutral plasma stream, drifting across magnetic field lines, with a velocity $\underline{E} \times \underline{B}/B^2$, penetrates into the region of higher magnetic field intensity B, the component of its bulk velocity parallel to the gradient of B is reduced adiabatically. Indeed as a result of conservation of magnetic moment, the translation kinetic energy of all drifting charged particles is adiabatically converted into gyromotion. This leads to specular reflection of the particles against the **fictive** surface of the magnetosphere. The adiabatic deceleration of plasma streams in regions with increasing magnetic field intensity has been first proposed by Chapman and Ferraro (Ref.44) and demonstrated experimentally in the laboratory by Demidenko et al. (Ref.45) (see also Ref.23 and references therein).

Closed and open steady state models of the magnetosphere, like those schematically illustrated in fig.5a, have had their supporters for a long time. None of these stationary interaction models has, however, been able to account for all observations collected from space as well as from modern ground-based geophysical stations.

It was in 1976, at a meeting in Amsterdam, that the idea of non- stationary and patchy interaction of solar wind with the magnetosphere was emphasized, probably for the first time (see Refs. 20 and 21).

The interaction model put forward in Ref.20, assumed that small scale eddies are formed by MHD instabilities at "funnel-shaped identations" along the magnetopause surface. According to the other non-steady state interaction model proposed in Ref.21 the observed small scale plasma irregularities are not necessarily produced locally in the magnetopause region : it was argued that there are already plenty of such plasma irregularities in the non-uniform solar wind rushing into the geomagnetic field ; the densest of these plasma elements or plasmoids are able to penetrate deeper into the magnetosphere than those with lower momentum flux density (Refs. 21, 22, 23). This second scenario, illustrated in fig.5b, is now known as the Impulsive Penetration (IP) theory of solar wind plasma density into the magnetosphere.

From high resolution interplanetary magnetic field measurements it was clear already in the 60's that the solar wind is non-stationary and non-uniform most of the time over periods as short as 5 seconds or distances of 2000 km (i.e. a few mean proton gyroradii). High resolution plasma measurements in the solar wind now available have confirmed this expectation inferred in 1976 from high resolution IMF observations.

Since the solar wind plasma is patchy, its momentum flux density over the surface of the magnetopause is neither uniform, nor stationary. Time dependent and non-uniform boundary conditions imposed from the outside by the variable and patchy solar wind, force the magnetospheric plasma, electric and magnetic fields to be non-stationary over periods of time of seconds.

This implies that the interaction between the solar wind and the geomagnetic field can not be described in the framework of D.C. electromagnetic field theory (i.e. the magnetostatic and electrostatic theory). The rapidly changing solar wind imposes a non-stationary description for this interaction : in other words A.C. electromagnetic effects have to be taken into account as claimed in Refs. 42, 43. This conclusion is similar to that reached in § 2A concerning the relevance of stationary reconnection models used to describe highly non-stationary explosive flare events.

The Impulsive Penetration Model briefly described in Refs. 21, 22 and 23, belongs to this second category. When diamagnetic solar wind plasma irregularities "rain" into the magnetosphere, like droplets into a water pound, they perturb not only the local plasma density, the ambiant temperature and ion composition, but, they also change continuously the local magnetic field intensity and its direction ; they perturb the local electric field, as a consequence of their relative motion with respect to the background magnetospheric plasma.

If A.C. electromagnetic effects are essential in the study of solar wind-magnetosphere interaction models, they cannot be described in the framework of slowly varying D.C. magnetostatic field line distributions like those generally used to sketch the topology of the magnetosphere or of Flux Transfer Events.

C. **Geophysical effects resulting from impulsive penetration of plasmoids in the geomagnetic field**

Intrusion of the most impulsive diamagnetic plasma blobs is controlled by the orientation of the interplanetary magnetic field. This is a consequence of the dipole-dipole interaction between the magnetic moment of the entering plasmoids and the magnetic moment of the Earth (Refs. 22, 23, 41).

Furthermore, while they are convected across magnetic field lines in the magnetosheath and in the magnetosphere with an injection drift velocity, $\underline{E} \times \underline{B}/B^2 = V$, the particles forming the penetrating plasmoids are eventually slowed down ; their injection (translational) energy, $1/2\ mV_i^2$, is converted into enhanced gyro-motion because of conservation of their magnetic moment, $\mu = mv_\perp^2/2B$. Their penetration velocity, $\underline{V}$, as well as $\underline{E}$, the convection electric field inside the plasmoids, eventually vanish when they have reached a place where the local magnetic field intensity B is such that all their translational energy has been transferred adiabatically into thermal motion perpendicular to the magnetic field direction (Ref. 23).

In addition to this adiabatic braking or slowing down of all particles forming the invading plasmoids, non-adiabatic (irreversible) dissipation of the injection energy takes place via Ohmic (Joule) heating in the dayside Cusp or Cleft Ionosphere (Ref. 21).

This distant energy dissipation heats the plasma at the low altitude feet of all the magnetospheric field lines which are crossed by penetrating plasma irregularities. This ionospheric heating of the plasma in the dayside clefts has been observed and is discussed in Refs. (30, 35). This is one of the clearly identified geophysical effects resulting from the solar wind-magnetosphere interaction.

Another geophysical consequence of Impulsive Penetration theory is the transfer of momentum to the ionospheric plasma in the high latitude trough regions and also to the magnetospheric plasma flowing around intruding plasmoids. This is rather analogous to the flow of any fluid along the surface of a penetrating object (Ref. 22, 23). The resulting poleward ionospheric motions have been identified and discussed in Refs. 31, 32 and 33.

The field-aligned propagation and dispersion of the ions and electrons forming the intruding plasmoids have also been observed and reported in Ref. 5. The description given for these magnetosheath particle injection observed in the dayside cleft fits nicely in the Impulsive Penetration scenario. They form an additional class of geophysical phenomena which are consequences of the non-stationary interaction between the solar wind and the Earth's magnetosphere illustrated in fig. 5b.

Other geophysical effects like field-aligned current systems and non-steady state convection flow patterns observed in the polar caps can be interpreted in terms of the theory of Impulsive Penetration of solar wind plasma irregularities in the magnetospheric tail lobes, when the Interplanetary Magnetic Field has a Northward component. These NBZ effects are described in Ref. 41.

There are many more geophysical effects which are linked directly or indirectly to solar wind conditions and to their time variations (see for instance Ref.24). For up to date and comprehensive reviews, see for instance Refs. 26, 27 and 28. All these phenomena are part of the wide ensemble of solar-terrestrial relationships. Some of these additional solar-terrestrial relationships are discussed in the next article and in other papers in these proceedings.

4. Conclusions

Let us conclude this necessarily incomplete review of solar-terrestrial relationships by emphasizing how much the Sun-Earth system is a floppy coupled physical system. The links are basically electromagnetic and corpuscular radiation at all wavelengths and at all energies. The intensity of these different fields of radiation are not only variable over periods comparable to the 11 years solar cycle, but they also change drastically over time scales of minutes and even seconds.

A lesson of this scientific endeavour could then be : although the assumptions of stationary and uniform flow have always been tempting and convenient for traditional modelers, these easy assumptions happen rarely to be applicable to the ever changing Sun, Solar Wind, Magnetosphere, Ionosphere, Upper Atmosphere ... and, of course, Solar Flares, Flux Transfer Events, or Magnetic Substorms.

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Appendix 1

Kinetic theory of solar wind acceleration in brief for slow and fast speed streams

As first pointed out by Chamberlain (Ref.11) the Coulomb collision mean free path of thermal coronal protons become larger than the characteristic density scale height, beyond a radial distance of 3 to 6 solar radii, depending on the energy of the colliding charged particles.

Beyond this radial distance, called the exobase level, the protons as well as the electrons can be considered to be collisionless (non-interacting ; at least in a zero-order aproximation) : their Knudsen number is larger than unity in the coronal ion-exosphere above the exobase.

All electrons and protons with velocities larger than the gravitational escape velocity (275 km/sec at 5 R_S), can in principle evaporate out of the gravitational potential well, assuming that collisions can be neglected in the ion-exosphere. But since the thermal speed is $\sqrt{m_p/m_e}$ times larger for the electrons than for the protons, the net escape flux should be 42 times larger for the electrons than for the protons. This draws a huge negative polarization current out of the solar corona. The positive polarization charge density acquired by the corona sets up a charge separation electric field and an overall negative electrostatic potential difference between the exobase and infinity : the plasma becomes polarized as a result of the tendency for the electrons to escape at a higher rate than the heavier thermal ions.

The electric potential difference decelerates the electrons and reduces the number of them which are able to escape out of the gravitational plus electrostatic potential well. This electric potential difference accelerates the protons outward, thus increasing their net escape flux and their kinetic energy.

It has been shown (Ref.12, 38) that the equilibrium value of this electric potential difference adjusts itself to obtain escape fluxes which are equal for the retarded electrons and for the accelerated ions. Since, for the protons, the equilibrium value of the accelerating electrostatic force largely exceeds their decelerating gravitational force, all H^+-ions are drawn out of the corona and obtain supersonic velocities at large heliocentric distances, as indeed, is observed at 1 AU.

It has been indicated in Ref. 13 that Chamberlain also would have been able to predict the observed supersonic proton bulk speed at 1 AU, instead of a subsonic solar breeze, if he had used in 1961 the electric potential distribution described above, instead of using the standard Pannekoek (Ref.17) - Rosseland (Ref.18) electric field which is strictly applicable only when a plasma is in hydrostatic equilibrium in the gravitational field.

The exospheric potential difference for which the net electron flux balances the net ion escape flux is equal to - 700 Volts when exobase temperature of the electrons and protons are equal to 1.4×10^6K (Ref. 12). When the coronal exobase temperature is larger than this typical value a larger electrostatic potential sets up to maintain net zero electric current ; consequently for larger coronal exobase temperatures, larger proton bulk velocities are expected at 1 AU, as well as higher plasma temperatures (Ref. 12).

The positive correlation between solar wind temperatures and bulk velocities which is predicted by this simple kinetic theory fits nicely the observations (Refs. 14, 15) in low speed solar wind regions (i.e. where the measured bulk speed is smaller than 400 km/sec) (see Ref. 13).

In high speed solar wind streams, originating in low density, low temperature coronal holes, however, quite the opposite result has been found. This indicates that present solar wind theories and models, including the MHD or fluid models, fail to give the observed solar wind features in flow regimes where bulk speeds are larger than 400-500 km/s.

We have recently been able to show (Ref. 16), however, that the presence of an additional outward flux of suprathermal electrons, besides the thermal escape flux of low temperature coronal hole electrons, increases the equilibrium value of the negative electrostatic potential difference between the corona and infinity. This enhancement of the electric potential accelerates the exospheric protons up to a bulk velocity of 600-700 km/s.

The "strahl electrons" mainly observed in low density high speed solar wind regions (Ref. 39), constitutes an additional subpopulation of suprathermal electrons. We have calculated that the flux of suprathermal "strahl electrons" is indeed large enough compared to the escape flux of the coronal hole thermal electrons to increase the solar proton speed up to 600-700 km/s i.e. up to the values observed in high speed solar wind streams.

Similar high-speed solar wind velocities can only be obtained in modern MHD or multi-fluid models when ad hoc heating of the solar wind is assumed between the 2 and 10 R_S. It is not yet clear, however, where this additional energy should come from, and, how it could be dissipated at the right place in the coronal plasma.

Further details on this new explanation of fast speed solar wind streams will be published elsewhere.

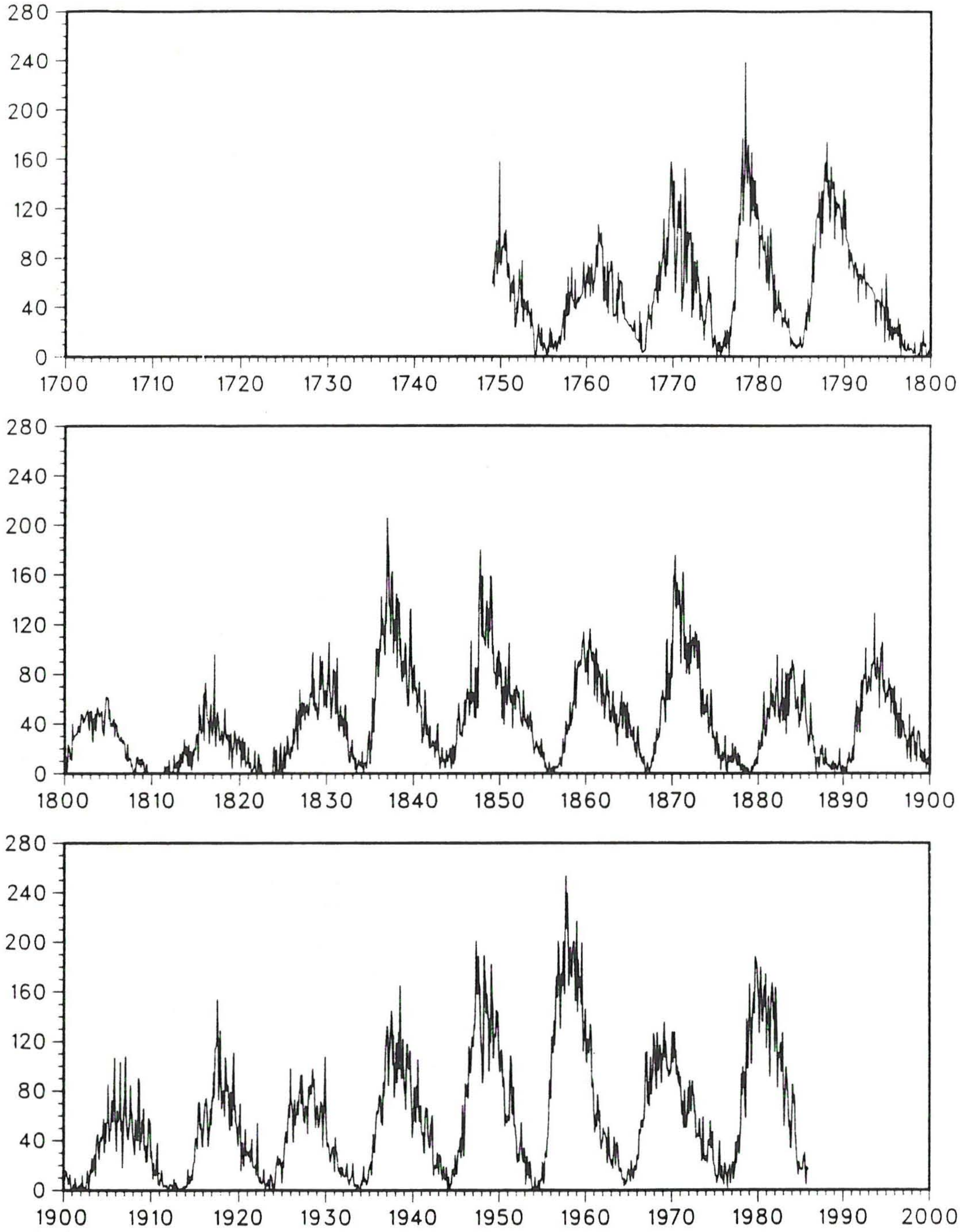
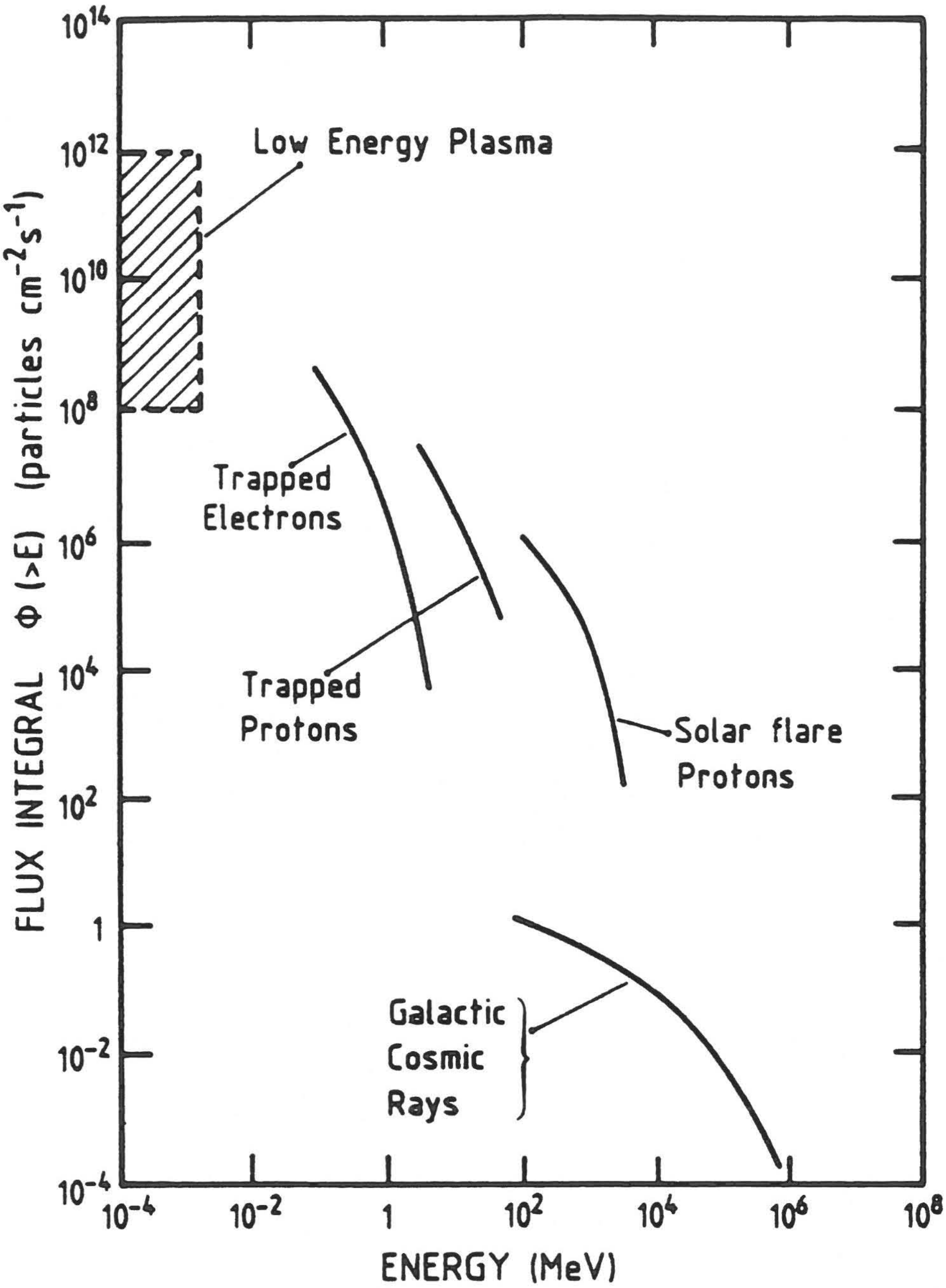


Fig.1 : MONTHLY MEAN SUNSPOT NUMBERS January 1749 - December 1985
Monthly mean numbers reveal the sunspot count's variability. Monthly averages also contain a 27-day fluctuation that reflects the rotation period of the sun and the uneven distribution of spot groups across solar longitudes. The largest monthly mean (253.8) occurred in October 1957.

(from NGDC, Boulder)



<u>Fig.2</u> : Typical energy integral flux of the different populations of charged particles in the Earth magnetosphere.

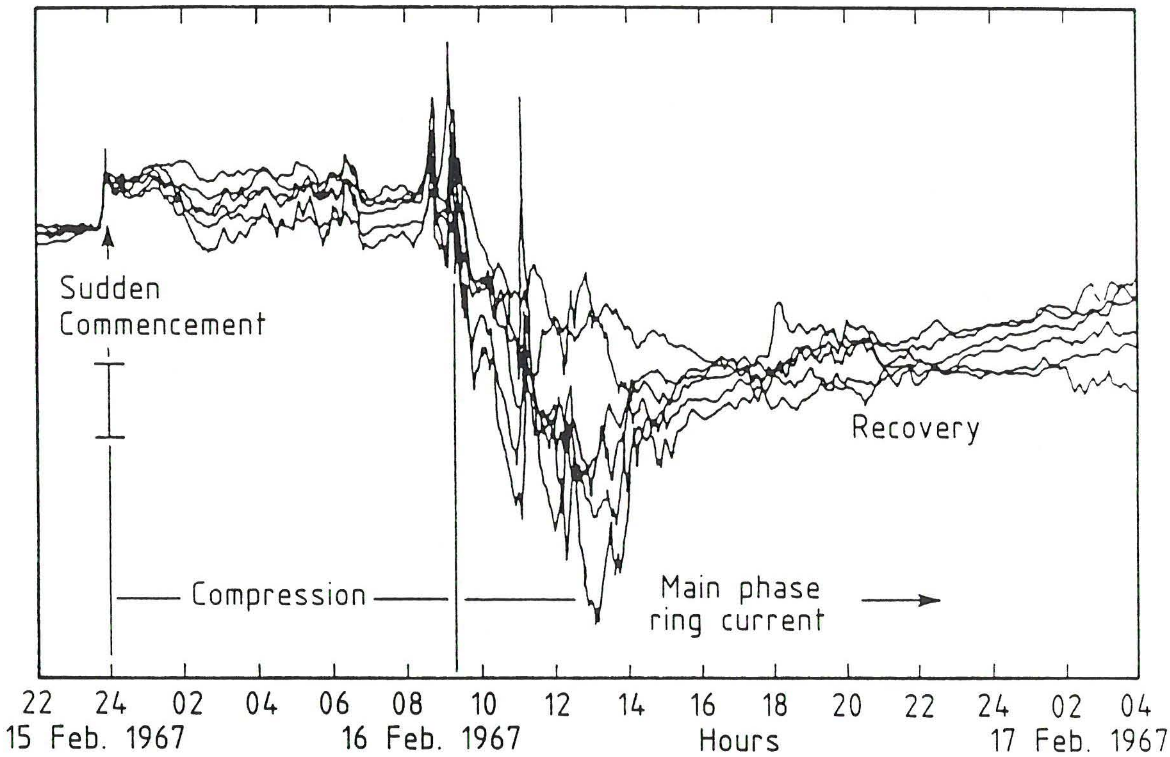


Fig.3 : A magnetic storm detected by the variation of north-south component of the magnetic field at six different magnetic observatories around the world. The "sudden commencement" and following sustained high field intensity results from the compression of the magnetosphere by an enhanced solar wind flow ; the pronounced decrease during the "main phase" is produced by the storm ring current that develops in the inner magnetosphere. Differences among stations are mainly due to longitudinal and local-time variations of the storm effects. (after Ref. 36)

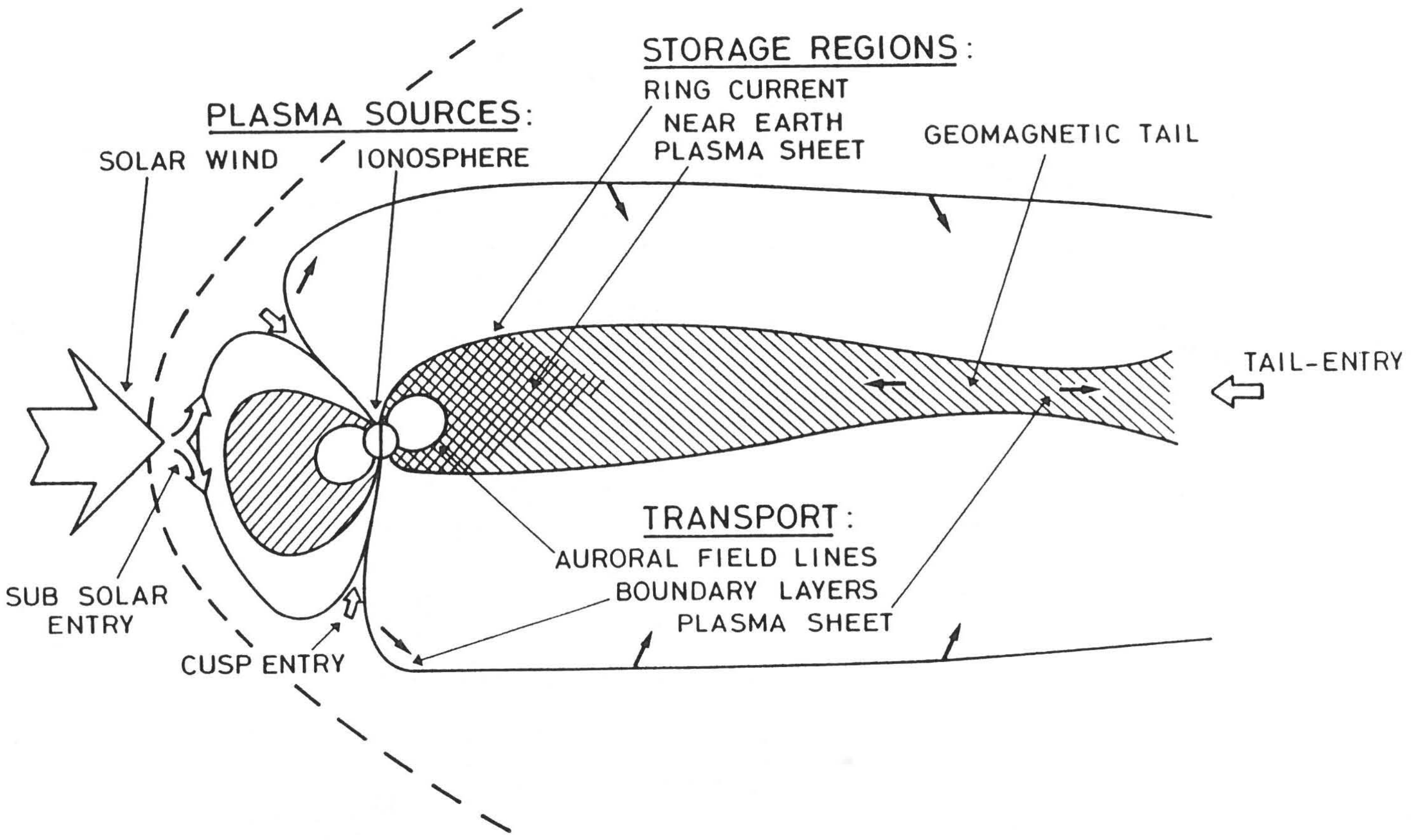


Fig.4 : meridional cross section of the Earth's magnetosphere showing different regions populated with charged particles of different energies and of different origins.

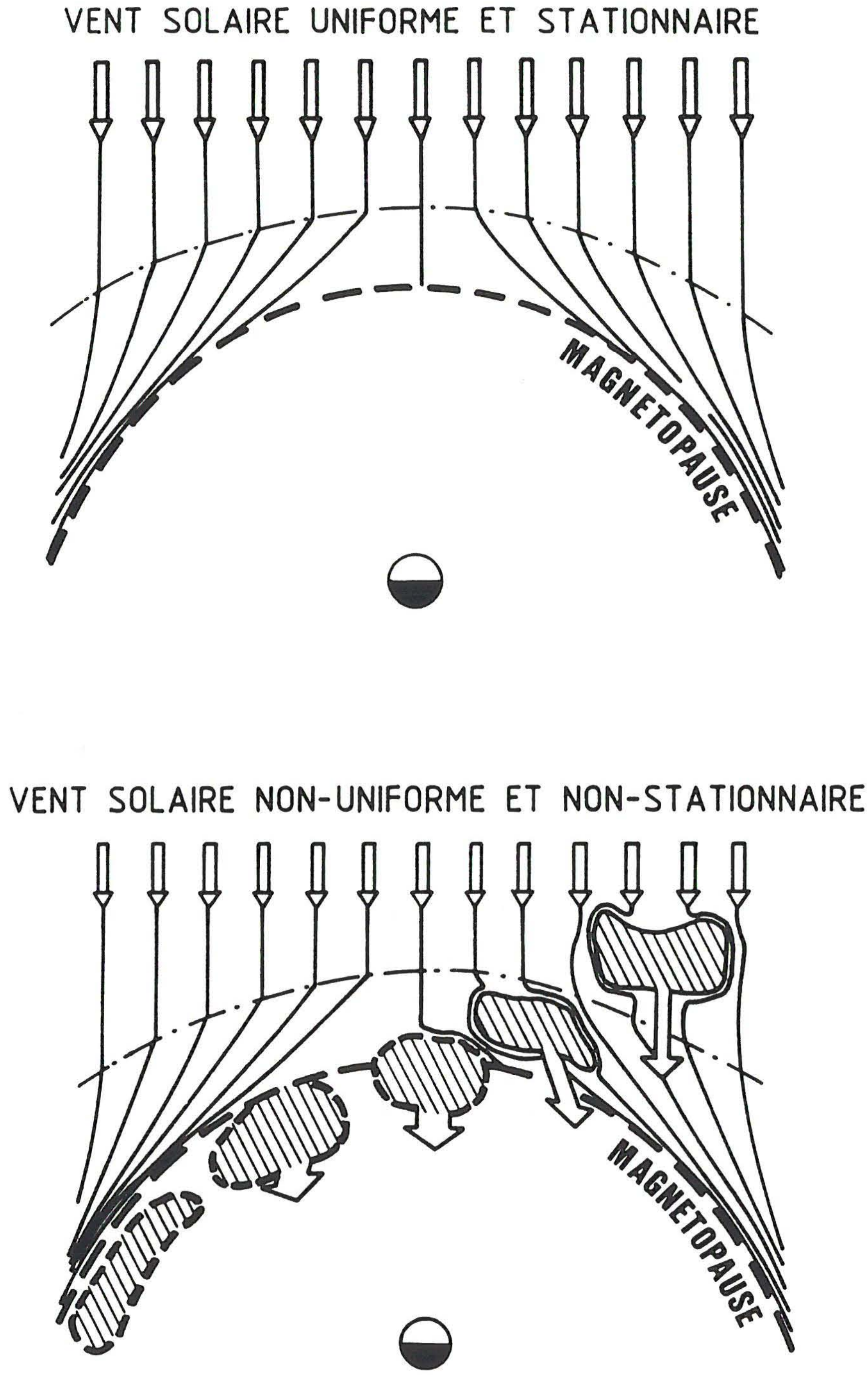


Fig.5 : a) Equatorial cross section of a steady state magnetosphere with quasi-stationary and uniform solar wind flowing around as in early closed and open magnetospheric models.

b) Impulsive penetration of plasma irregularities present in solar wind plasma and raining continuously into the Earth geomagnetic field. As a result of their relative motion with respect to the magnetosheath and magnetosphere plasma, these intruding plasmoids induce time-dependent (A.C.) electric and magnetic field perturbations, which cannot be described in the framework of DC electrostatic and magnetostatic theory and quasi-stationary field line distributions ! (after Ref. 21)