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Chapter 8

THE SPACE OBJECT OF MAGNETOPLASMA: MAGNETOSPHERE OF EARTH.

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1. QUIET MAGNETOSPHERE AND PERMANENT DISTURBANCES

The name magnetosphere was used for the first time by US physicist Thomas Gold [Gold, 1959]. He wrote "The region above the ionosphere in which the magnetic field of the earth has a dominant control over the motions of gas and fast charged particles is known to extend out to a distance of the order of 10 earth radii; it may appropriately be called the magnetosphere".

The Earth's magnetosphere can be divided into three parts, namely the internal, external one and one situated in between – the auroral magnetosphere. During the disturbances the differences between the individual parts manifest especially heavily.

Magnetosphere is a very dynamical formation. It is continuously variable with motions of its boundaries. The dynamics is reflected in the aurorae, magnetic disturbances as well as in particle and plasma dynamics which is measured by the artificial satellites of Earth. All disturbances can be divided into three types. In this subchapter we describe composition of the quiet magnetosphere, its regions – domains, and the borders between, observed during the quiet time periods.

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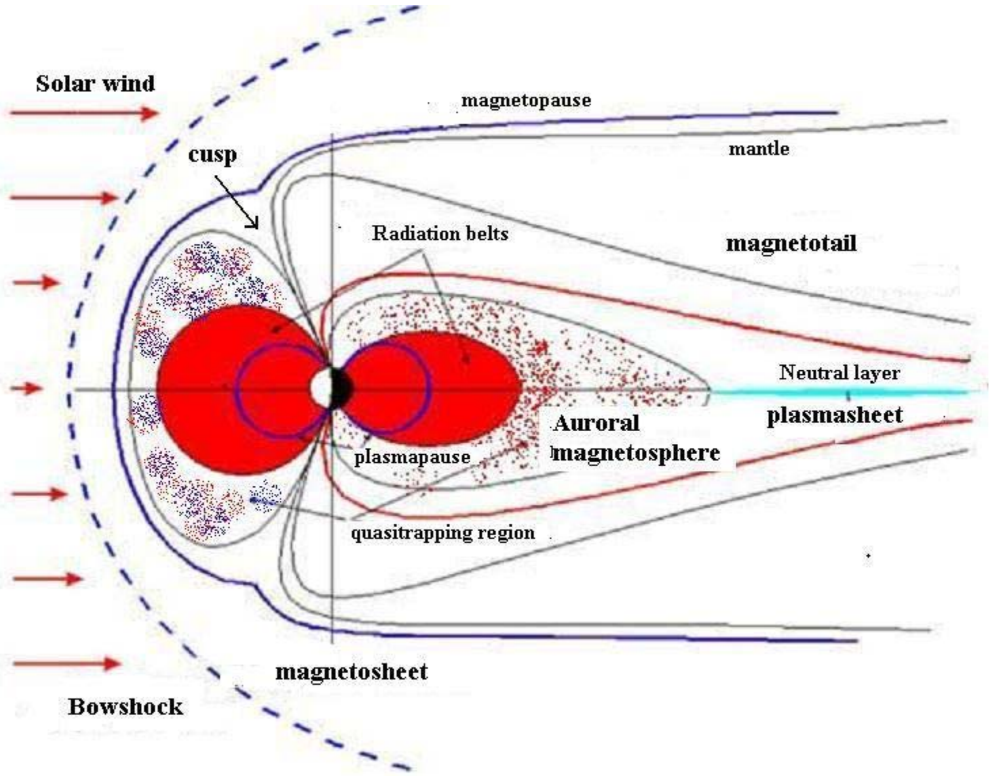

Figure1.1. Schematic view on meridional section of magnetosphere with the regions discussed.

The schematic picture of the magnetosphere is represented in Fig. 1.1. Magnetic field tubes of the magnetosphere are filled by plasma and by energetic particles. Plasma structures or domains begin from the *ionosphere* which is from its inner side built into the *atmosphere* of Earth, and from its outer side passes fluently to the *plasmasphere*. The outer border of the plasmasphere, plasmapause, separates it from the plasma sheet. Simultaneously the plasma sheet is divided into two parts – tail or boundary plasmasheet, and auroral or central one, which are situated according to definition in the tail and in auroral magnetosphere.

Energetic particles reside in the *radiation belts*, and episodically in the *auroral magnetosphere*. The region of its appearance out of the belts has been named by the team of N. S. Vernov as the zone of instability radiation. However, this term was not established often. More frequently the term *auroral radiation* is used. Finally, the whole formation is surrounded by the threefold boundary layer, composed out of the Earth’s bow shock, magnetosheath and magnetopause.

The magnetospheric boundaries are not seen from the Earth, but the other regions are projected along the magnetic field lines through the ionosphere to the Earth’s surface.

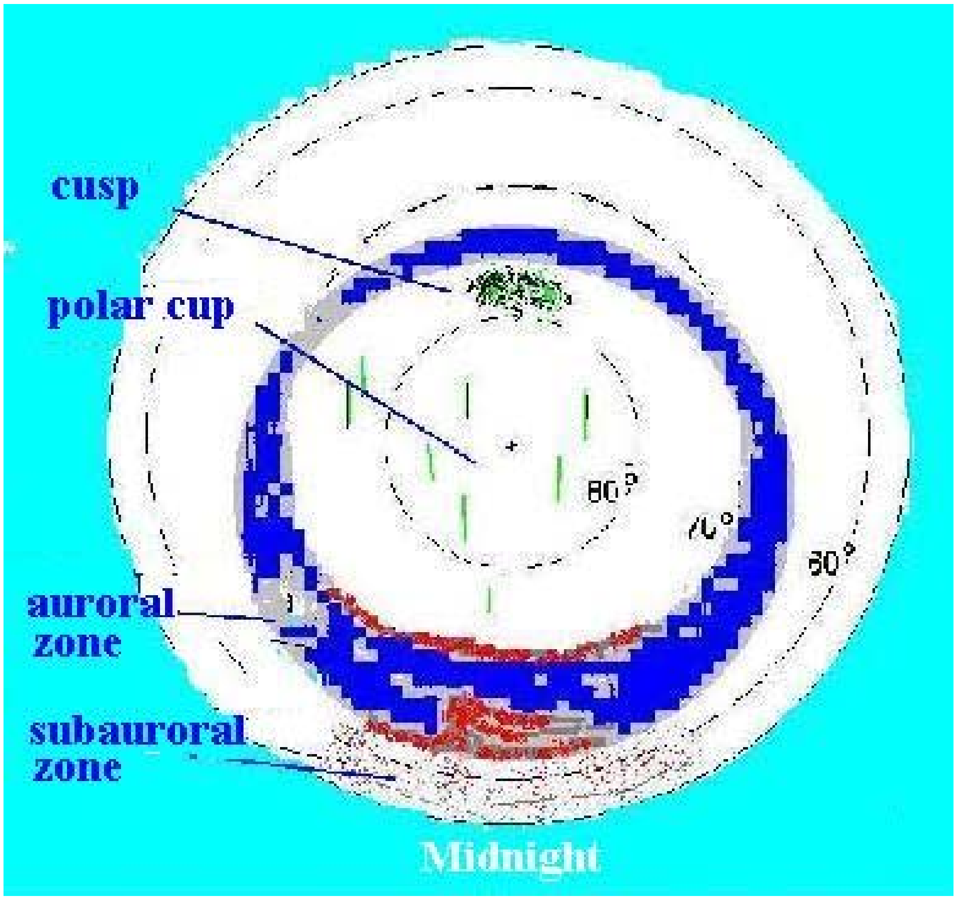

Figure1.2. The projections of magnetospheric regions to the Earth.

The field lines dragged out to the geomagnetic tail are projected to the polar cap. On the dayside the region named cusp adjoins to that – a “horn” of field lines outgoing into free space. The auroral magnetosphere is projected upon the zone of auroral emissions (Fritz zone). The subauroral zone where weak radiance driven by the precipitation of electrons from radiation belt is observed is situated at lower latitudes. Later all the domains mentioned above will be discussed along with the details of permanent disturbances identified by the recent observations.

1.1. Magnetospheric Boundaries

Due to the interactions of solar wind impinging on the Earth’s magnetosphere, the *Earth’s bow shock* is originated. Closer to the Earth the *magnetosheath* separates it from the *magnetopause* being the boundary of the magnetosphere which screens or makes uneasy the access of charged particles into the inner regions of magnetosphere from outside. The exception presents the *cusp* (more exactly two cusps, northern and southern one), the funnelled opened outlet for solar wind particles into the confined region of polar cap. Sometimes that region is forcing out into the band named as *cleft.*

Earth's bow shock. Still before the Space Era it became to be clear that if the solar plasma is flowing via the Earth's orbit, the Earth's magnetic dipole presents an abstacle for the flow. Chapman and Ferraro (1931) formulated schematic physical model of the interactions of plasma with the extrinsic body. When the plasma cloud swells on the geomagnetic field, the electric current is induced inside. Current is producing itself the magnetic field which destroys the normal geomagnetic field inside the cloud and, at the same time, it is amplifying normal field in the region between cloud and Earth. The cloud is stopped when its momentum is consumed on the compression of geomagnetic field. The emergent boundary is called the Earth's *bow shock*. Position of the sub-solar point during the quiet time is about 10 Re, while during the disturbances it approaching to the Earth down to 5-6 Re depending on the solar wind pressure.

The boundary of magnetosphere (magnetopause) is determined by the balance between magnetic field pressure and pressure of the swelling plasma.

In the *magnetosheath* situated between the bow shock and the magnetopause, the dense (n=10-30 cm^{-3}) and cold plasma both in the solar wind (100 eV) is strongly different from the rarefied (n=0.3 cm^{-3}) and hot (from 0.5 to several keV) plasma inside the magnetosphere. The layer adjacent to the magnetopause from the inside is transitional layer with parameters of the cold plasma similarly to those in the magnetosheath. In the vicinity of polar cusps the transitional layer is named as *entry layer,* at high latitudes in the magnetotail it is called *plasma mantle* and at low latitudes it is denoted as *plasma sheet boundary layer* (PSBL). The existence of the transitional layer means that solar wind plasma invades into the magnetosphere, and consequently it hands over its energy.

In the magnetosheath the plasma is strongly turbulized and this circumstance may endorse the interconnection between the magnetic field lines of the solar wind and those of magnetosphere. There are interconnected not all but only selected force tubes. Along with the solar wind moving around the Earth, the tubes are transferred on the night side, into the magnetotail, and, along the tubes the solar wind plasma is penetrating into magnetosphere.

1.2. Radiation Belts

The first flights of satellites in former USSR and in US discovered the existence of regions in space with substantial increased flux of energetic particle in comparison with the neighborhood. These regions have been denominated as Van-Allen belts or radiation belts of Earth.

Figure 1.3. [Kuznetsov, 2007] depicts radial profiles of the trapped fluxes in the regions of detection of electrons and protons in the Earth's magnetosphere obtained by the scientists onboard four satellites named Electron (1 to 4) launched in the former USSR, namely by Yu. I. Logachev, E.N. Sosnovets, S.N. Kuznetsov and others working in the Skobeltsyn Institute of Nuclear Physics, Moscow State University during geomagnetically quiet times, when in the first approach the trapped fluxes are represented by the symmetry of belts in longitude [Logachev, 2008].

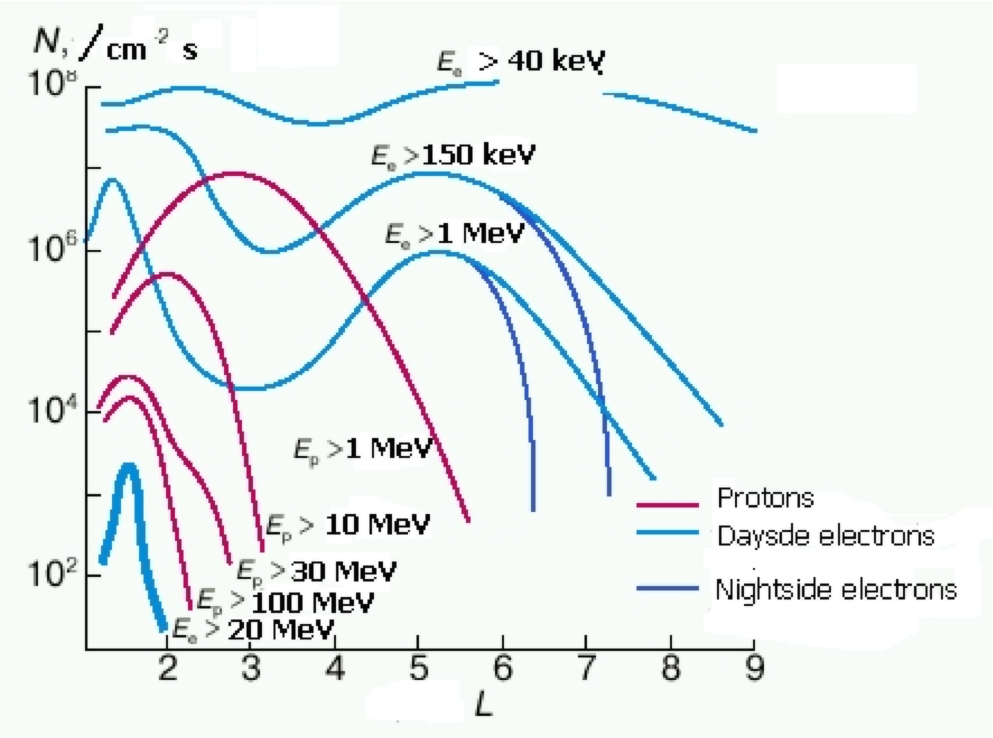

Figure1.3. L-shell profiles of the trapped proton and electron flux in the magnetosphere**.**

The electrons with kinetic energy > 100 keV create two belts, namely the inner one at L < 2.5 and the outer one at L > 3 with the *trough* at L=2.5-3.5. The radial profile of protons has no trough. With the decrease of L the protons of higher energies are more abundant. Radiation belts are one of the diversities of the geomagnetic trap.

Motion of the charged particle in the magnetic and electric field is controlled by the Lorentz equation

$$\boldsymbol{F} = \boldsymbol{F}_e + \boldsymbol{F}_m = e.\boldsymbol{E} + q.\boldsymbol{v}x\boldsymbol{B}$$

Sometimes by the Lorentz equation just the term $\boldsymbol{F}_m$ is understood. This force controls the trajectory of charged particle. At low energies when guiding center approach can be used, the trajectory consists of three types of cyclic motions, namely (a) the gyration around the field line, (b) bouncing between the mirror points on opposite hemispheres, and (c) azimuthal magnetic drift around the Earth. The particle is stable trapped if its guiding center is completing at least one full cycle of azimuthal drift along the closed drift trajectory. This is valid when the first, second and third adiabatic invariants are conserved. The theory and details of the motion of charged particles in dipolar-like geomagnetic field can be found e.g. in books [Roederer, 1970; Schulz and Lanzerotti, 1974; Lyons and Williams, 1984].

The structure and composition of radiation belts have been described many times. Thus we do not stand at this point in details.

1.3. Auroral Magnetosphere

Starting from a specific radial distance, the particles drifting from the night side of Earth do not complete the full turning cycle, and come out at the magnetopause on the morning side (electrons) or at the evening side (ions). Similar region outside of the stable trapped one is also on the dayside and both are called *quasitrapping region*, and corresponding particles are denoted as quasi-trapped in the case so long as their trajectory can be described as superposition of the gyration, bounce and longitudinal drift.

In the quasitrapping region, namely in the domain of decreasing intensity of radiation belt particles, there is observed several particle populations: particles of plasmasheet with energy 1 – 2 keV, auroral electrons and ions with energy of units to hundreds of keV. Flux of freshly accelerated auroral particles during the substorms is often exceeding the background flux of "old" particles of radiation belt by several orders. Further these particles are either lost in the atmosphere, or move out to the magnetopause, or fill additionally the radiation belts via the process of radial diffusion. Quasitrapping region as a domain of possible development of magnetospheric substorms is called the auroral magnetosphere.

Figure 1.4 [Lazutin et al., 2007] shows the examples of energy spectra of electrons in the range of energies 0.1 to 100 keV measured by satellite CRRES in a 5 min interval during geomagnetic substorm. Low energy part of the spectra (a) is filled from the ionosphere and it is strongly variable. In the energy range from 1 up to 5-10 keV the central plasmasheet region follows (b). At highest energies (c) there are electrons of radiation belt with addition of auroral electrons. While in region (c) the energy spectra has a power law character, at lower energies it has mainly (not always) Maxwellian shape.

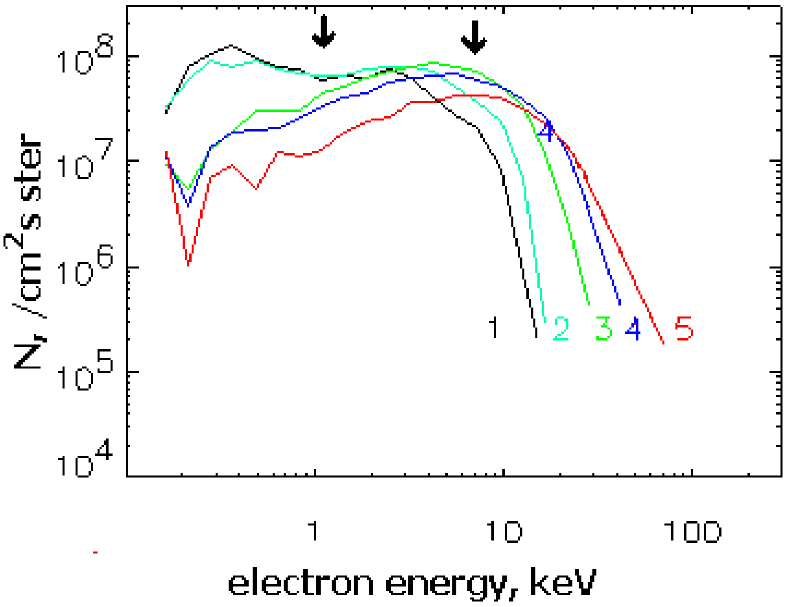

Figure 1.4. CRRES measurements of energetic electrons during a substorm.

The auroral magnetosphere, the region of polar storms, represents projection of the instantaneous zone of active aurora, the auroral oval proposed by Feldstein and Khorosheva.

Auroral zone. Figure 1.2 shows the zone of auroral emissions (ring zone) by a ring shifted towards the night. In the night time sector it is situated in the range of latitudes 60° - 70° where the bright and dynamic auroral forms are observed. During the periods of increased geomagnetic activity the southern boundary is shifted towards middle latitudes and the northern one enters into polar cap.

Central plasmasheet represents a part of the auroral magnetosphere. Here the energy of particles is enhanced up to several hundreds of keV, the density and energy is variable. Particles accelerated during the substorms are seed particles for filling-up of the radiation belts.

Spatial distribution of plasma is inhomogeneous. The illustrative delineation of the inhomogenity is seen by *auroral arcs*. A homogeneous arc, the discrete or diffusive one, represents the fundamental property of the plasma organization within the plasmasheet, or more precisely, of the structure of the magnetosphere – ionosphere coupling . The electric potential across the auroral arc has a specific structure of inverted V. Satellite crossing the arc, first observes increase of energy of the electrons causing the emissions. Next, the energy decrease is seen by the satellite. Most probably the inverted V is not creating the arc, but it is accompanying phenomena of the arc. The extent of the discrete arc is about few hundreds of meters, however the dimension of the inverted V in the projection on the ionosphere is typically 30-35 km.

1.4. Plasmasphere

The ionosphere of Earth, above the altitudes 1000-2000 km smoothly goes over to *plasmasphere* – region filled with the cold plasma which is rotating along with the Earth due to the action of the corotational electric field. Plasmasphere is overlapping with the radiation belts. The outer boundary of plasmasphere is called the *plasmapause*, which is separating plasmasphere from the plasma sheet, where the plasma particles are moving by the convective electric field. Plasmapause has a larger distance from Earth in the evening sector due to the course of the drift of ions. During the quiet time periods it is seen the evening convexity, which during the intervals of strong geomagnetic storms is crossing into the so called *plumes*.

1.5. Geomagnetic Tail

The existence of geomagnetic tail was predicted in 1960 by J. H. Piddington and investigated in detail by the measurements of Norman Hess on satellite IMP-1 in 1964.

Geomagnetic tail comprises structures depicted schematically in Figure 1.1. In its central part there is *neutral sheet*. On either side of that the magnetic field lines of force has the opposite direction. The neutral sheet of geomagnetic field inheres in the center of plasma sheet boundary layer (PSBL) which was mentioned in 1.1. Above the PSBL there are situated formations named *lobes* where the low density of plasma is compensated by the enhanced value of magnetic field strength. The outer sheet of the lobes adjacent from the inside to the magnetopause is called *plasma mantle*. Figure 1.5. shows two schemes of the cross section of geomagnetic tail at distances approximately 8-10 and 15-20 Earth radii.

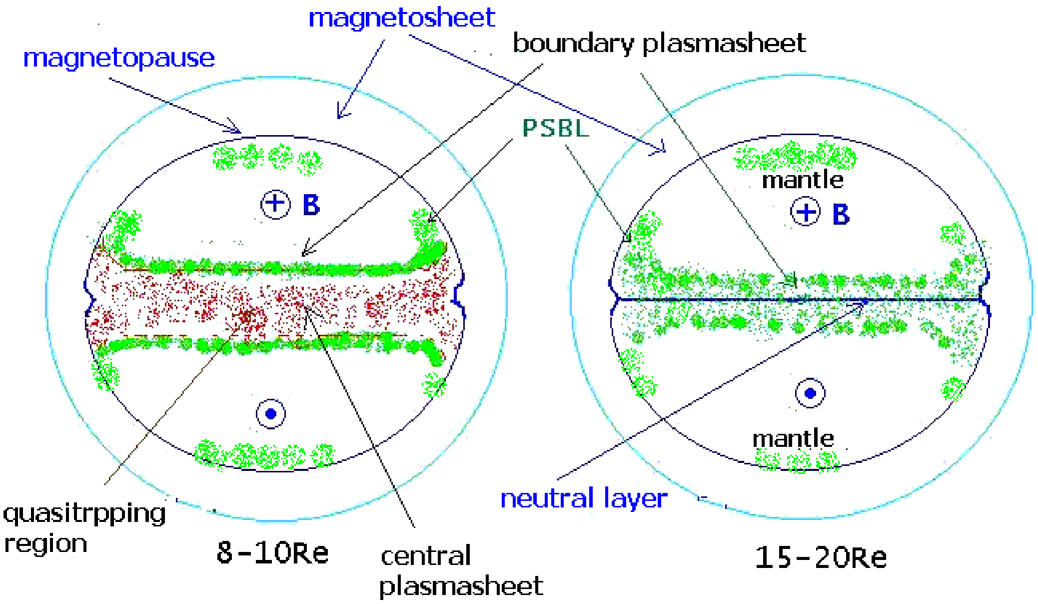

Figure 1.5. Geomagnetic tail sections with the specific regions at two different distances from Earth.

In the more distant section there are depicted all plasma sheet formations mentioned above, while in the section closer to Earth the auroral magnetosphere along with its inner plasma sheet are seen.

For the quiet time intervals there are characteristic disturbances denoted as permanent. It is due to the fact they are present practically continuously. Radiation belts and auroral magnetosphere are not intervened by permanent disturbances. The effects of permanent disturbances are characteristic for geomagnetic tail and for polar cap.

Geomagnetic tail occurs always in motion. Onboard the satellites the wave-like structures of the tail, the elevations and falls-off in position of the plasma sheet and neutral sheet – so called flapping motions, have been observed. Along with that, the radial flows of plasma – tailward the plasmoids and Earthward the fast fluxes of plasma (FFP) are observed regularly. The occurrence of plasma flows is usually related to the processes of *reconnection.* Geometry of magnetic field with antiparallel field line structures in plasma is unstable, fast reconnection of the field lines is possible and “annihilation” of magnetic field with the release of large amount of energy for the acceleration of charged particles occurs. Reconnection process enters as a substantial point into one of the models of magnetospheric substorm, and earthward motion of the plasma structures can be a carrier or trigger of substorm which is developed in the auroral magnetosphere.

Permanent disturbances in polar cap have been discovered according to the measurements of magnetic disturbances on the ground much earlier than by the in situ measurements on satellites in the geomagnetic tail. The auroral structures are dragged out in the meridional direction. Each arc is observed for a rather short time interval of few minutes with low intensity, sometimes at the subvisual level. Sometimes the wave-like disturbances mostly directed to the Earth are running along the arc. According to the measurement of altitude of the radiance the conclusion is deduced that the arcs are created by the electrons with energy 200-400 eV. Short time slight variations of geomagnetic field correspond to the occurrence of aurora.

The distant end of the tail and signatures of plasma sheet are observed as far as to the orbit of the Moon (> 100 Re).

Due to effect of solar wind in the plasma mantle and in the low latitude boundary layer at the flanks of magnetosphere the vortice of convection is created. It has sunward direction at the flanks and earthward direction in the center. The electrodynamic force of the generator may be created by the quasi-viscous interaction with the solar wind, and/or by the reconnection at magnetopause. Tail and auroral plasma sheets are mixed up by virtue of the action of convective electric field. Particles of plasma sheet are penetrating from the tail to the vicinity of Earth, to the quasi-trapping region, where they act as reservoir particles which after acceleration provide supply for the radiation belt populations, cause the auroras and geomagnetic disturbances.

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2. GEOMAGNETIC SUBSTORMS

The energy of solar wind enters into magnetosphere continuously. However, if the rate of energy transfer is not high, it is released in the geomagnetic tail via the permanent disturbances. If there are created separated portions of accelerated, enhanced entry and such process is maintains more than 40-70 minutes, magnetosphere releases the energy stored by the explosive manner. Such process is called geomagnetic substorm.

Proverb "sub" means it is of second order in comparison with global storm which is in principle not true. The polar storm is not less, but may be more complex than the global storm. Several special experiments with 3-5 satellites launched simultaneously were performed but still substorm complexity did not allow to the community of researchers to come to the agreement in understanding of the mechanisms of the substorm. For the questions how, where and why substorm begins and how it is evolving - there exist two basic and several additional models which we mention at the end of this subchapter. In the following part we devote the attention to the experimental data measured from the Earth's ground and in space.

2.1. Preparatory (Growth) Phase

Processes originated during the growth and active phases are substantially different. That is why they are assumed as two different effects. Growth phase is the process of inflation or storage of solar wind energy into magnetosphere, while substorm represents breaking off in this process. Process of inflation is not always necessarily finished by the substorm. It may be finished by pseudobreakup, disturbance of the type "saw tooths" or convective bay.

Energy of substorm.. Elementary substorm involves scenario in view of slow loading of energy and its faster unloading. How it proceeds and what does it mean? Storage of potential energy in the magnetosphere – it is changes in geomagnetic field. Field lines are stretched further into geomagnetic tail, the field force is decreasing or increasing in some region(s). This represents storage of potential energy. When the magnetic field is coming back to its normal conditions, the electric field is induced according to rotE=-dB/dt, and when the charged particles are present, potential energy is converted into kinetic one.

Any forced change of the dipolar magnetic field, both its increase or decrease, leads to the increase of potential energy. There existed an assumption that before the substorm the energy is stored only in parts of the geomagnetic tail, because the field force there increases. From that asumption originated checking of the beginning of substorm in the tail and from that the problem of energy transfer into auroral magnetosphere was discussed. Rightly the decrease of magnetic field in auroral region leads to the release of basic part of substorm energy, and in the parts of the tail there is deficit of particles and the acceleration is not important for energy release. Changes of magnetic field is provided by the specific system of currents, currents are equivalent to the motion of charged particles and particle motion is controlled by the electric field. Such is the chain.

Bz-component of IMF. From where takes the energy in preparatory phase? From solar wind – it is kinetic energy of solar wind plasma. The rate of energy transfer increases substantially when IMF is oriented southward (Bz<0). S.-I. Akasofu [1968] introduced index of efficiency of action of the solar wind on magnetosphere

$$\varepsilon = \mathbf{Btr}^2 \bullet \mathbf{V} \bullet \sin^4(\theta/2),$$

where

$$\mathbf{Btr}^2 = \mathbf{By}^2 + \mathbf{Bz}^2$$

$\theta = \tan^{-1}(\mathbf{By}/\mathbf{Bz})$ **V** – solar wind velocity.

Such configuration of IMF is favorable e.g. by reconnection of field lines, when direct penetration of solar wind plasma into magnetosphere is possible, or creating the convective vortice inside the magnetosphere via viscous friction. As a result, the increase of large scale electric field occurs. However in that subject there is no consensus yet among the researchers. There is also question whether magnetopause or magnetosheath is important for the induction. How the field is passing through these regions? Another opinion is that convection is of minor importance and particles in the geomagnetic tail are moving chaotically.

Model of growth phase. This phase can be conceived in the following way:

The convective electric field is rapidly enhanced (from 20 kV to 80 kV across the magnetosphere,

from east to west).

The acts of reconnection in the geomagnetic tail occur more frequent, hot plasma particle population at the border between auroral magnetosphere and tail is increasing.

The electric field drives the plasma from the boundary of the tail towards the Earth, temperature increases from ~ 200 eV to 1-3 keV due to increase of magnetic field along the trajectory (betatron effect).

Field lines of magnetic field are stretched, magnetic field induction in the auroral magnetosphere is decreasing.

2.2. Beginning of the Substorm. Explosive Activation

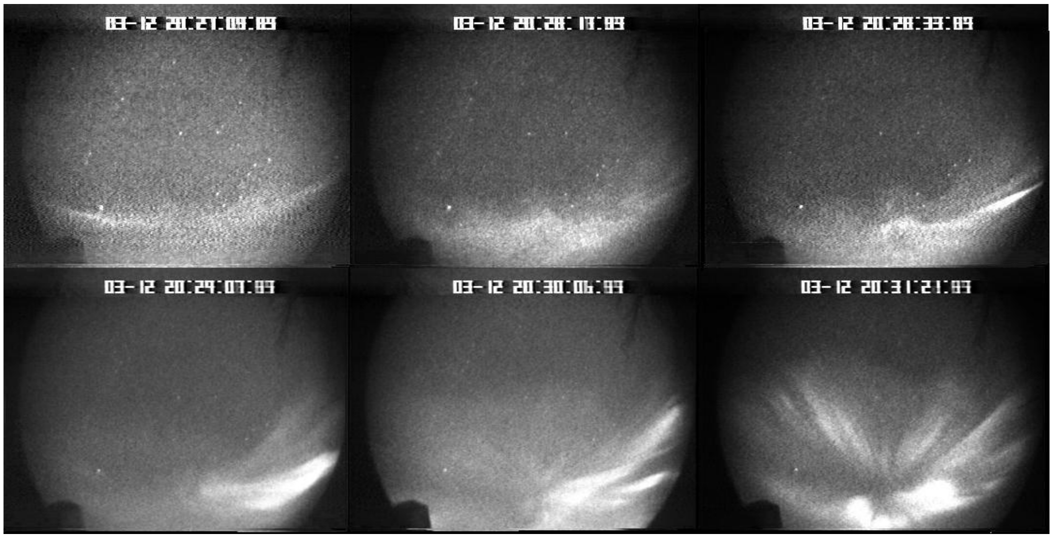

Figure 2.1. Photograph of evolution of the break-up of aurora. North is to the top of figure.

The main brightest and clearly seen event of the explosive instability of substorm is break-up in the auroral emissions. Fig. 2.1. shows six snapshots of aurora made by the all sky camera during the break up. On the first one there is seen quiet arc. Which of the five consecutive is fixing the time of break-up, depends on point of view of interpreter. Quite often the time of break-up is determined with accuracy of 1-2 min. But to understand how the starting instability is evolved, it is necessary to go over to 1 sec resolution.

However, improvement of time resolution reveals large diversity of the emission patterns. Even with resolution of fractions of second allowed by cameras it is difficult to identify undoubtedly the time of the beginning of event. However, what means the beginning of the event?

Auroral emissions are ground, or more precisely ionospheric secondary manifestation of the acceleration processes of auroral particles precipitating from the trapping region. May be it is necessary to examine in more detail the dynamics of particle flux? The auroral particles are of two types, namely (a) particles of central plasmasheet with energy few keV, and (b) suprathermal particles with energy from ten to hundred(s) of keV. Assuming that not always electrons and ions are accelerated identically, we will results with four populations of substorm particles or more frequantly called auroral particles [Lazutin, 2007].

The central event of the beginning of substorm is supposed to be the process of explosive release of stored energy – *activation* [Lazutin, 1998] which consists of the chain: fast dipolarization of magnetic field; generation of induced electric field; charged particle acceleration. As a result, potential energy stored in the form of distortion of magnetic field, is transformed into kinetic energy of particles.

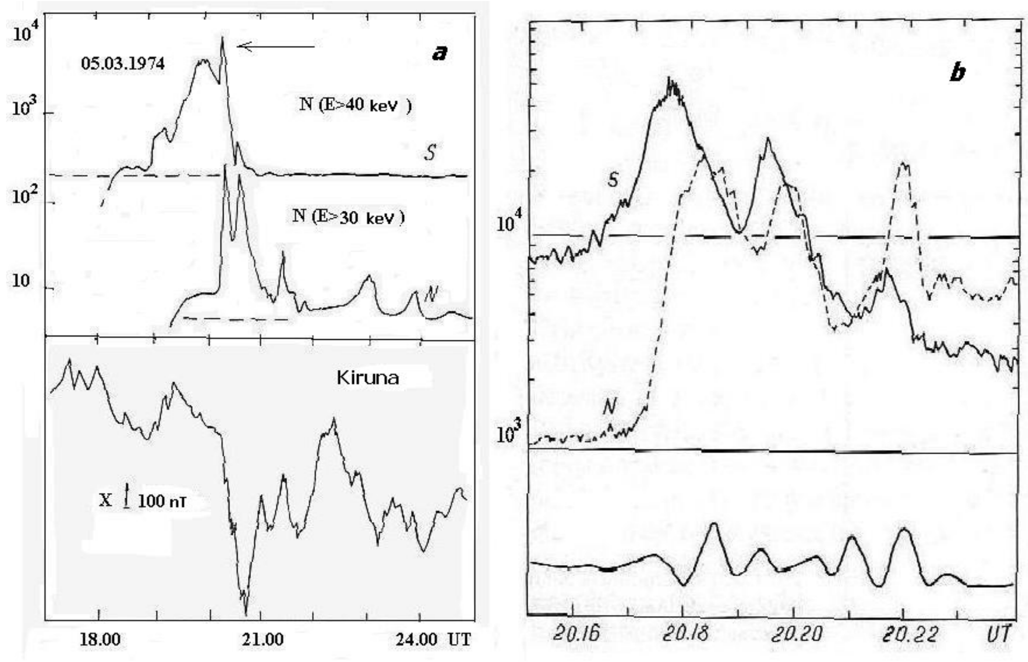

Figure 2.2. Measurements of X-rays at two balloons with mutual distance 100 km during the experiment SAMBO. Right panel is a zoom with better resolution indicating the disturbance at magnetometer (a) and geomagnetic pulsations of the type Pi2.

2.3. Energetic Auroral Electrons

As a first part of the chain it was discovered acceleration of energetic electrons (energy from 20 to 200-300 keV). Fig.2.2. shows the measurement of fast bursts of energetic electrons in stratosphere [Lazutin, 1986]. Balloons did not observe electrons (they are lost not succeeding to reach altitude 30 – 35 km), but the X-ray bremsstrahlung. Fast bursts of X – rays with accuracy of 1 minute coincided with the magnetic bay and increase of brightness of aurora.

The activation is not a single one, but multiple bursts are typical. Contrary to the auroral emissions where break-up pictures are mixed in the indiscernible vortice, the activation of energetic particles easily underlies to the structural patterns, and thus picture of the substorm is better distinguishable. Usually one activation prepares the second one and the region of activation is shifted westward and toward the pole. The corresponding process is called *polar expansion*. The *fragmentation* of the substorm, longitudinal limitation of the active region is also one of the properties of the substorm.

In the magnetosphere at the equatorial plane, the activation includes the extent of 5-10 Re at the descent region of outer radiation belt of electrons. Increase of particle flux during the activation was reported according to CRRES measurements. The analysis of substorms observed by energetic particle detector on CRRES revealed that almost all activations are situated in the quasitrapping region [Lazutin and Korth, 1998]. Variability of energetic particle flux during one substorm is shown in Figure 2.3.

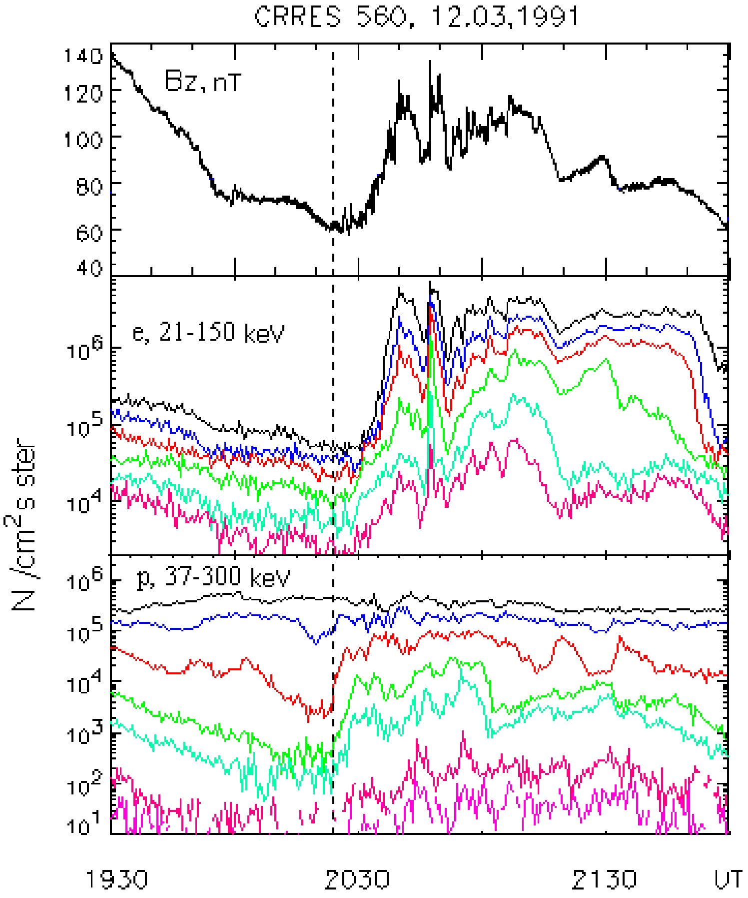

Figure 2.3. Middle latitude fluxes of energetic ions and electrons and magnetic field according to measurements on CRRES satellite during the substorm March 12, 1991 [Lazutin et al., 2007].

It is seen that dipolariization of magnetic field takes place in coincidence with increase of flux of energetic electrons. Electric field induced by the variation of magnetic field is difficult to measure because it is required to stay exactly in the local region of equatorial plane. Low altitude satellites do not see it because along the field lines there is "transmitted" only potential electric field. However, the changes, impulses in the magnetic field producing induced electric field, are observed frequently. Thus there are seen all the three components of the process of activation, namely dipolarization, electrodynamic force and acceleration of electrons [Heikkila and Pellinen, 1977; McIlwain, 1974; Nishida, 1978].

2.4. Fine Structure of Break-Up

There are, however, events which are excluded from the scheme mentioned above, namely energization of protons for couple of minutes before the start of activation which is seen in Figures 2.3 and 2.4 which took place together with increase of low energy electrons along the magnetic field lines.

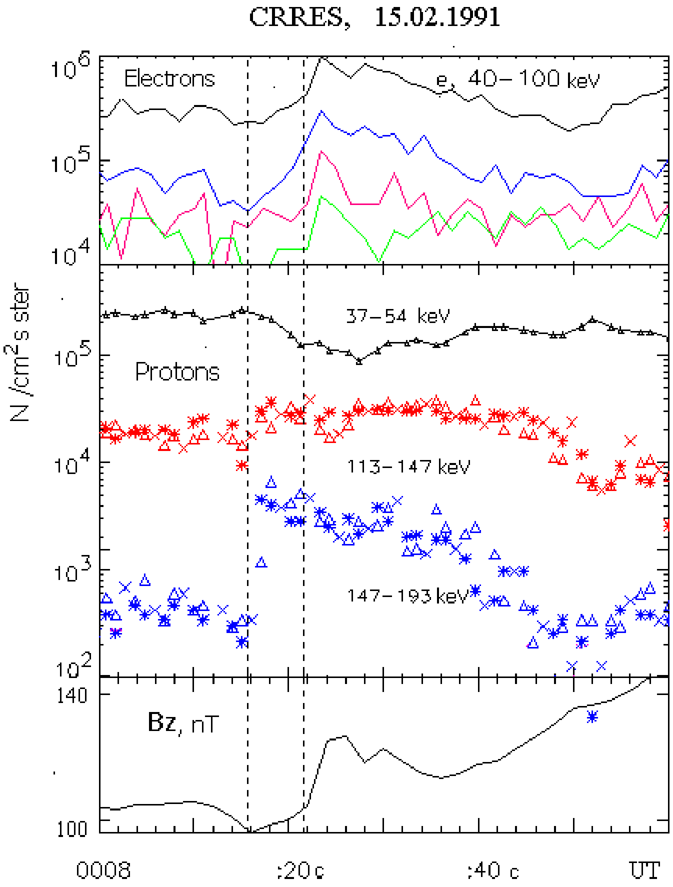

Figure 2.4. The same as in Figure 2.3 for the substorm February 15, 1991. The increase of electron flux coincides with the increase of Bz component which is a signature of dipolization, reaching its maximum at 0008:22. However, 9 seconds before the huge abrupt increase of protons is apparent [Lazutin, 1998a].

Low energy particles are accelerated along the field lines connecting magnetosphere with the ionosphere and thus the majority of particles have small pitch angles. During the activations there appears anomalous resistivity in local regions along the field lines. Thus along the field lines occurs the potential. Its value obtained from measurements is up to several kV with the direction which accelerates electrons moving towards the Earth and ions towards the equator. Thus precursors of the activation are indicated: field aligned fluxes of low energy electrons and increase of energetic protons. Appearance of enhanced flux of energetic ions leads to the local decrease of magnetic field force – effect observed by [Ohtani et al., 1998] and called as *amplified growth phase*. It is observed just before the activation. The same is stretching of magnetic field lines in the sunward direction. Such stretching distorts the rests of balance and leads to the triggering of activation.

The effect of energetic proton enhancement before the activation may explain amplified growth phase effect, but it is still necessary to explain why this enhancement took place and how it is related to the field-aligned low energy electron fluxes.

There are some suggestion on this subject but not yet many measurements of such type, however, they are promising in clarifying initial processes of substorms.

Because during the time of dipolarization additional acceleration of energetic protons drifting eastward occurs, they can create a new focal spot of instability, to initiate the second activation, and consequently the other activations of the chain.

2.5. Development of Active Phase and Recovery Phase

After the break-up the activity pervades to all directions northward, southward, eastward and westward. Northern direction is most brightly expressed, especially during the first 10 – 15 minutes. This period is called polar expansion. On keograms (created by extracting vertical pixel columns from individual all-sky images and putting the columns side by side) the polar expansions are clearly seen (Figure 2.5).

In the depicted keogram the polar expansion is clearly seen. Pulsations Pi2, which is one more framer of the beginning of the substorm, reflects the chain of activation in the current system of ionosphere (lower panel of Figure 2.5).

The widening of the active zone in the nigh sector is well examined from the space. Although the fine structures are not seen on most of the pictures of aurora obtained from satellites because of relatively long time of exposition (~ 1 min), the evolution of large scale auroral emission regions is obtained (e.g. by POLAR satellite). Further, the active zone is enhanced variously for different events. The acceleration of particles leads to supply of region of quasitrapping and to the enhancement of drift flux, which are restoring the stretched structure of field lines. This leads to the secondary activation in those regions where the activation already took place.

The exact fixing of the beginning and of the end of recovery phase of the polar storm is impossible. In some localized regions recovery to the quiet configuration begins instantly after the first break-up, while in the others the active zone is still burning.

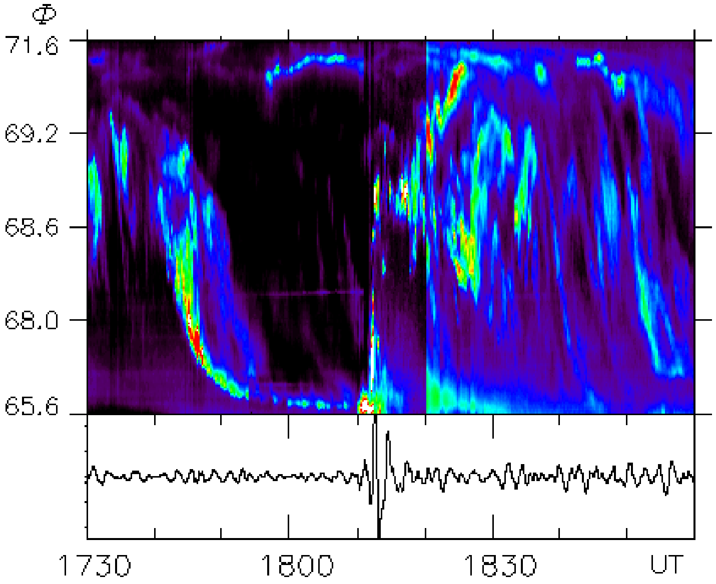

Figure 2.5. Keogram of aurora: subsequently in each vertical line there is meridional profile of brightness of aurora (black – absence of emission, red is maximum). Lower panel shows the geomagnetic field pulsations observed on the same observatory. [Lazutin, 2007].

Magnetosphere finally sheds from the excess of energetic particles during the interval not shorter than one day. In the release of electrons from outer radiation belt the basic role plays the cyclotron resonance. At present there is accumulated large amount of experimental materials on pulsations of aurora, on geomagnetic field pulsations, VLF emissions as well as on precipitation of energetic particles. Along with that the theoretical works and computer modeling of the processes are done by various authors.

2.6. About The Substorm Models

There exist two models of substorms, according to which the process of explosive release of the stored energy takes place either in the geomagnetic tail or in the auroral region, on the closed field lines.

Substorm in the geomagnetic tail. For rather long time dominated the idea that the beginning of activation is related to the specific point in the geomagnetic tail, namely to the point of reconnection of field lines. Really, the parallel and opposite directed field lines stretched into the geomagnetic tail may reconnect as it is seen schematically in Figure 2. 6. in the reconnection point. As a result the strong induced electric field accelerates charged particles, on both sides from the reconnection point the plasma flows are running and raise the aurora etc. [Hones, 1978]. Left panel of figure 2.7. shows the scheme of substorm evolution in the magnetotail according to V. Vasyliunas.

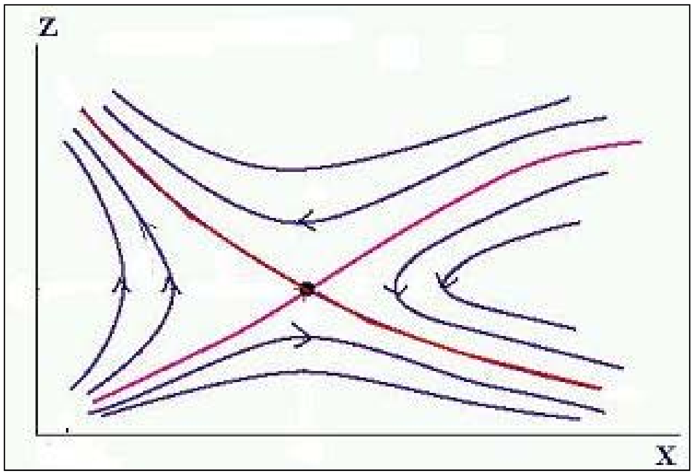

Figure 2.6. Scheme of reconnection of magnetic field lines.

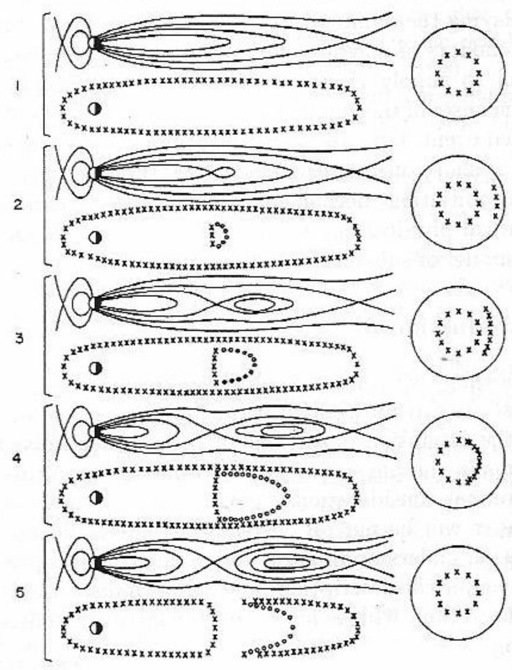

Figure 2.7. Scheme of evolution of substorm due to reconnection in the geomagnetic tail. Numbers in left denote stages of development in time, for each stage the cross sections in meridional plane noon – midnight and in the equatorial plane, as well as in the projection on ionosphere of Earth.

The reconnection starts at stage 2, the flux of plasma, so called bursty bulk flow (BBF) flows earthward, later plasmoid is formed in the geomagnetic tail, which separates and flows in the antisunward direction (stage 5).

Large amount of experimental works devoted to the understanding of evolution of substorms have been completed. Special groups of satellites with numerous devices are directed to such type of studies, e.g. Interball, Geotail, Cluster, Themis. Really, at distances 15-30 Re there are observed bipolar magnetic impulses indicating motion of plasma from the reconnection point, whereas for motion tailward there is observed first positive and next negative sign of impulse of Bz, while for the motion earthward the reverse sequence of polarities is reported. The earthward displacement is characteristic by the increase of Bz and depression of Bx, which corresponds to dipolization after which there must follow the explosive events. The main remaining problem is a relation of the magnetotail reconnection processes to the substorm development in the auroral magnetosphere.

Substorm in auroral magnetosphere. According to the second model the beginning and evolution of the substorm – both is starting in the auroral magnetosphere, in the projection – at the inner boundary of auroral oval. During the thinning of plasmasheet the ions lose the adiabaticity, they move from morning to evening according to so called serpentine orbits and in the interaction with adiabatically moving electrons in opposite direction, they generate low frequency waves, splitting the auroral arc into separate fragments. The conductivity in this sector decreases, current across the tail is disrupted and it is comprising through the ionosphere [Lui et al., 1992]. Contrary to the first model, the wave of disturbance, instability, is moving from the Earth to the geomagnetic tail.

Until now there is no unambiguity of the relation reconnection – substorm. Hot plasma flows are observed much more frequently than substorms (almost once per 10 min). Further, they are stopped at the gradient boundary between the closed and open field lines of the tail. Here the velocity of magnetic drift is larger than radial velocity, plasma is stored at stopping boundary, far not reaching the southern boundary of auroral magnetosphere, where the substorm starts. In the aurora this boundary corresponds to polar arc (one can see in on fig 2.5). Only with the delay during enhancement of convective electric field this plasma begins to move earthward, preparing the substorm. Most probably the reconnection can just generate an impulse which is triggering the substorm, in the same manner as sometimes the substorm is triggered by SC impulse if that is occuring at the end of preparatory phase.

Along with direct measurements in the geomagnetic tail, substantial success s was reached by theoreticians, e.g. in IKI RAS there was developed theory of reconnection, applicable for other cosmic objects, by the group of L.M. Zelenyi.

2.7. Summary

Substorm represents process of explosive transition of the stored potential energy of geomagnetic field in the auroral magnetosphere as well as in the geomagnetic tail to the kinetic energy of charged particles, which is consequently consumed to the supply of radiation belts, ionization of the ionosphere and heating of the atmosphere. Storage of energy takes place every time when IMF with field lines frozen in solar wind has favorable direction with negative Bz component.

In the two sentences above there is summarized the zero order understanding of the processes of substorm. In the understanding of processes of polar storms the progress in the past is remarkable, however, the definite clarification of the mechanisms behind this complex phenomena in magnetosphere is not reached yet.

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3. GLOBAL MAGNETIC STORMS

Contrary to substorms, when the explosive phase follows after the period of slowly storage of energy, in global storms it is reversed – at the beginning strong disturbance, hit of a solar wind with high speed - resulting in compressed configuration of magnetic field, followed by a slow recovery, relaxation. In the name “magnetic storms” there is reflected its sudden beginning. First we describe processes influencing on configuration of magnetosphere – in the solar wind plasma and electric field, currents and fluxes of particles and of plasma inside magnetosphere. After that we discuss how magnetospheric processes influence the population of electrons and protons in the radiation belts, and briefly we mention briefly the effects on ionosphere.

3.1. Phases of Magnetic Storm and Solar Wind

Figure 3.1. shows the typical record by near-equatorial magnetometer during the magnetic storm which starts by *SC* (sudden commencement), an impulse in geomagnetic field driven by the compression of subsolar magnetospheric boundary due to impact of high speed solar wind. This moment is fixed by the geomagnetic observatories and tables of times of SC along with reliability of its identification are forwarded to the world data centers.

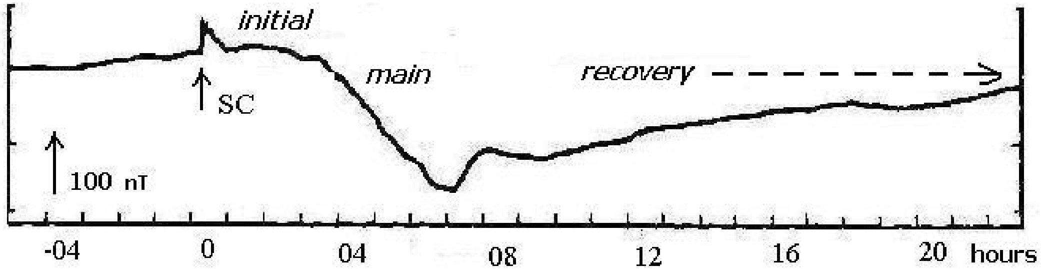

Figure 3.1. Basic phases of evolution of the global geomagnetic substorm according to record of variation of H-component of the conditional near-equatorial magnetometer station. Between the time of end of main phase and beginning of recovery phase, there is often observed transitional period with significantly increased ring current and with its repeated enhancements.

Phases of Geomagnetic Storm

Initial phase of the storm — time interval of the duration from several minutes to ten hours since SC until occurrence of southward component of IMF. When Bz becomes negative, the large scale convective electric field in magnetosphere is enhanced and the main phase begins.

Main phase of magnetic storm starts from the time of depression of horizontal component of geomagnetic field and it is finished, when depression is stopped.

Recovery phase may begin just after the main phase is completed, or some time later – it is related to the fact that when the group of sunspots appears, the series of flares of various power starts, and the solar wind speed on Earth's orbit can be of complex character with fine structure. Often happens that before the end of the first storm, the second or third one is reflected in geomagnetic field record. This means that rather often between the main phase and recovery phase there is a gap of the type of intermediate phase.

Decrease of H-component is observed practically simultaneously at each of the near-equatorial stations. This implies that the storm is driven by the current, surrounding the Earth at distance 3 – 5 Re in the equatorial plane. It should be mentioned that storms are clearly recognized at low and middle latitude stations, however, in the auroral zone the profiles of changes connected to the storm, have substantially different character due to the occurrence of auroral disturbances, the substorms discussed in previous section.

Basic indicator of the power and dynamics of magnetic storm is Dst-index, reflecting power of ring current. Dst is computed by the summation of magnetograms from 4-6 equatorial stations, distributed by longitude, and it is provided for the worldwide community by the World data center in Kyoto, Japan at the site http://swdcwww.kugi.kyoto-u.ac.jp/index.html.

Weak storms are named those reaching Dst in (-30nT to -50 nT), the moderate (-50nT to -100nT), strong (-100nT to -200nT), severe (-200nT to -350nT) and great have in the minimum value Dst < -350 nT.

Action of solar wind. The frequency occurrence and power of the magnetic storms is determined by solar wind. According to the the origin the magnetic storms are divided to recurrent (i.e. repeated) and sporadic (i.e. unexpected) ones.

As per effects in the magnetosphere the two types are not very different, and both their effect on radiation belts is significant. However, according to origin and relation to the Sun, they are differentiate. Sporadic storms are caused by the solar flares, by the coronal mass ejections related to flares and with high sped solar wind structures. The recurrent storms are interconnected with coronal holes (old notation – with M regions) which exist on the solar surface during 2-3 solar rotations and are repeatedly occurred on Earth with ~ 27 day periodicity. Fig. 3.2. shows the characteristics of interplanetary medium and geomagnetic activity index for one rather active interval.

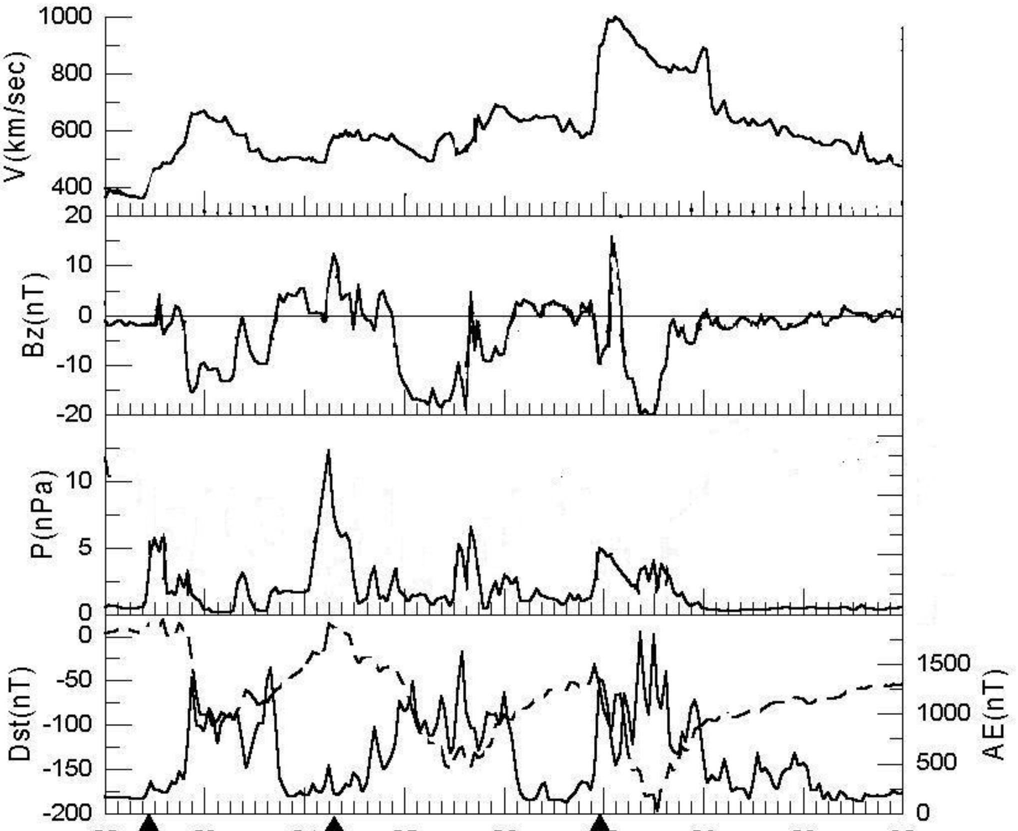

Figure 3.2. Parameters of solar wind and indices of magnetic activity during a chain of strong geomagnetic substorms. [Kuznetsov et al., 1998].

Figure 3.2. shows solar wind speed, Bz component of IMF, solar wind plasma pressure and Dst for a series of geomagnetic storms in July 2004. AE is auroral electrojet index is designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. It is provided at http://wdc.kugi.kyoto-u.ac.jp/aedir/index.html site. The SC impulses are denoted by triangles at the bottom.

All SCs are accompanied by jumps of solar wind plasma pressure (p) indicating the access of high speed solar wind to the Earth's orbit. Appearance of negative Bz of IMF does not follow immediately after SC, but it causes the onset of the main phase of all three storms of the July's chain of storms. The main phase is accompanied by the high substorm activity. Just after Bz is dropped to zero, the main phase is changed by the recovery phase.

3.2. Ring Current

The progress of the main phase is determined by the enhancement of the ring current. Ring current is electric current carried by the trapped charged particles. It is caused mainly by the longitudinal magnetic drift of particles with energy 10 – 200 keV. Additional action affords the fluxes flowing along the surface of the magnetosphere in its auroral part which comprise magnetosphere to the ionosphere. According to the extent of storm development the contribution of different components is changing. First the ring current is not closed at all, its protons are accelerated in the night time sector, and they drift towards the evening side. Protons of ring current only close to the end of main phase become to be distributed along all longitudes. Formerly in the midnight-evening sector of local time the maximum of flux is originated. Recently the Kyoto WDC for geomagnetism started to provide the axially symmetric and asymmetric components of geomagnetic activity indices (SYM, ASY). In addition to protons, significant contribution of O+ ions in the ring current was identified by the measurements. This indicated that the ions flowing out of the atmosphere (ionosphere) is important component of the ring current. From where the increased fluxes of energetic ions originating the ring current are coming to L = 3-5? Apparently they are coming from the peripheral magnetosphere and undergo the acceleration to energies up to tens of keV or more. Their transport towards the Earth is caused by ExB drift during the periods with enhanced large scale electric field in the direction east – west. Figure 3.2. shows the example of the estimate of electric potential required for such radial transfer.

Electric field increases by one order from the quiet value typically equal to 25 kV up to 250 kV during the active phase of the storm. Along with that there exist also another scenario, namely that one in which the substantial role is played by the substorms.

Southward component of the IMF (Bz) is necessary and sufficient for the expansion of global storm and substorm.

As it is known from analysis of substorms, during the activation there takes place radial transport of auroral particles along with acceleration towards the Earth, what is necessary for the formation of ring current. Since there are usually several substorm activation during a single substorm, and the substorms follow in succession one by one, the transport to L = 3-5 is quite possible, rather more that during the storm there proceeds widening of the auroral zone and the shift of its equatorial boundary towards lower latitudes, wher the activation takes place.

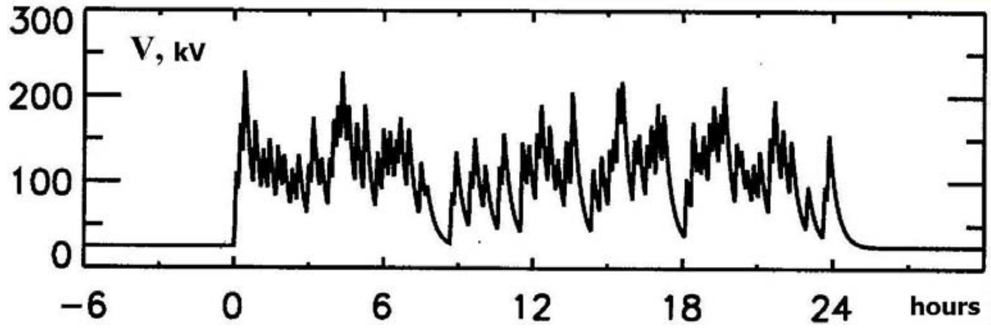

Figure 3.3. Example of computed electric potential across the geomagnetic tail during a geomagnetic storm (adapted from [Chen et al., 2000]).

In the model of ring current formation via the substorms there is one drawback. Such model does not clarify why during the recovery phase, when the substorm activity is still continuing, ring current is disrupted, not supported by the substorms. After the measurements of ring current composition, this model obtained support. There was observed significant enhancement of oxygen ions O+. This enhancement is as high as during the maximum of storm the oxygen ions contribute by 60-75% to the total ring current content [Kamide et al., 1998]. The source of oxygen ions is only the Earth's ionosphere, since in the solar element composition there is deficit of oxygen. Accordingly, the O+ ions have to escape from the ionosphere, to arrive consecutively into the magnetosphere and to be accelerated via the radial transport towards the Earth. Especially during the substorms there is produced electric potential along the field lines, the substorm current vedge, and fluxes of ions along the field lines coming out of the ionosphere, are observed. The interesting difference of substorms during the global storms from the isolated substorms was found [Baumjohann et al., 1996]: dipolarization is faster, the induced electric field is stronger and, consequently, the radial transport of ions is acting deeper during storms. It is observed just after the break-up ion transport reaching 50^{o}, while for the "usual" substorms it is less and more stretched in time.

Recovery phase of geomagnetic storms is connected with the decay of ring current. Basic mechanisms of particle losses are Coulomb scattering and charge exchange between energetic protons and neutral hydrogen producing energetic neutral atoms by reaction $\mathbf{H^{+}+H<==>H+H^{+}}$. Oxygen ions are lost faster due to its higher cross-section for ionization by the collisions with atoms of residual atmosphere. During the recovery phase there continues rather often the substorm activity and acceleration of energetic protons as well as relativistic electrons of radiation belts is observed.

3.3. Configuration of Magnetosphere

During geomagnetic storms the magnetosphere of Earth is strongly disturbed. Two processes are causing the distortion – enhancement of solar wind pressure and development of ring current. Due to the increase of ring current, in the inner magnetosphere the closed and almost dipole-like magnetic field lines are stretched, the tension weakens, energy density of magnetic field goes down, and the pressure of particles is increasing. As a result the belt of energetic electrons, the auroral magnetospheric boundary, the plasmapause as well as boundary of solar cosmic ray penetration are shifted towards the Earth (in the projection to ionosphere to lower latitudes).

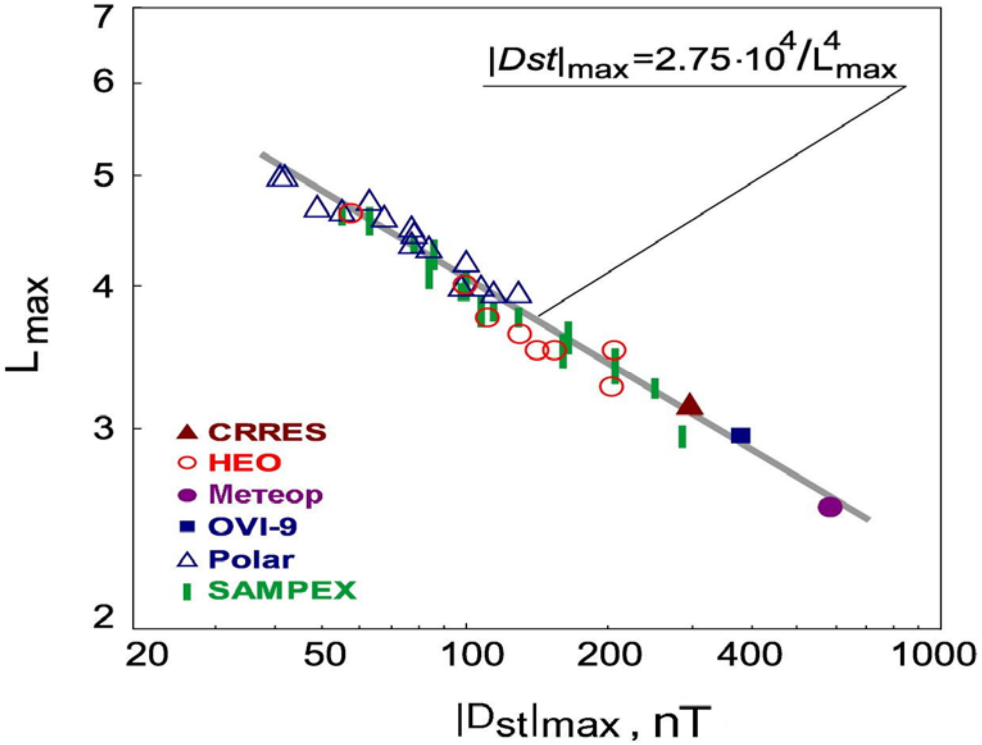

Figure 3.4. From [Kuznetsov and Tverskaya, 2007]. The dependence of the position of maximum of outer electron radiation belt depending on minimum Dst during various storms, deduced from various satellite measurements.

Position of the boundary of electron and proton penetration from interplanetary space to magnetosphere depends on the level of geomagnetic disturbance. Figure 3.4. is illustrating that.

Although the trend in figure 3.5. is clear (decrease of invariant latitude of the boundary with increase of Kp), the dispersion of latitude values for given Kp (3-hour single, global characteristic) is rather large. Sometimes still before the main phase of the storm it is observed maximum compression of the magnetosphere just due to the sharp increase of solar wind pressure.

Models of the field. Geomagnetic field is usually represented as a superposition of internal field (approximated by IAGA model IGRF – International Geomagnetic Reference Field) and the field of external current systems. There are several models of external current systems. In the first models presented by N. Tsyganenko there was supposed Kp in given ranges as a parameter. One of the newest models, namely TS04 [Tsyganenko and Sitnov, 2005] , was constructed for description of configuration of magnetosphere during geomagnetic storms. Dynamics of the magnetosphere is determined by the superposition of six current systems in addition to internal field: the tail field; the field of a symmetrical ring current; the field of partial ring current; the fields of region 1 and 2 of Birkeland current systems; and a penetrated component of IMF given by interconnection term. The contribution of each current system depends not only on instantaneous characteristics of the interplanetary space, but also on its prehistory. The configuration of the magnetospheric field lines seems relatively sufficient for the moderate storms but questionable for the strong ones.

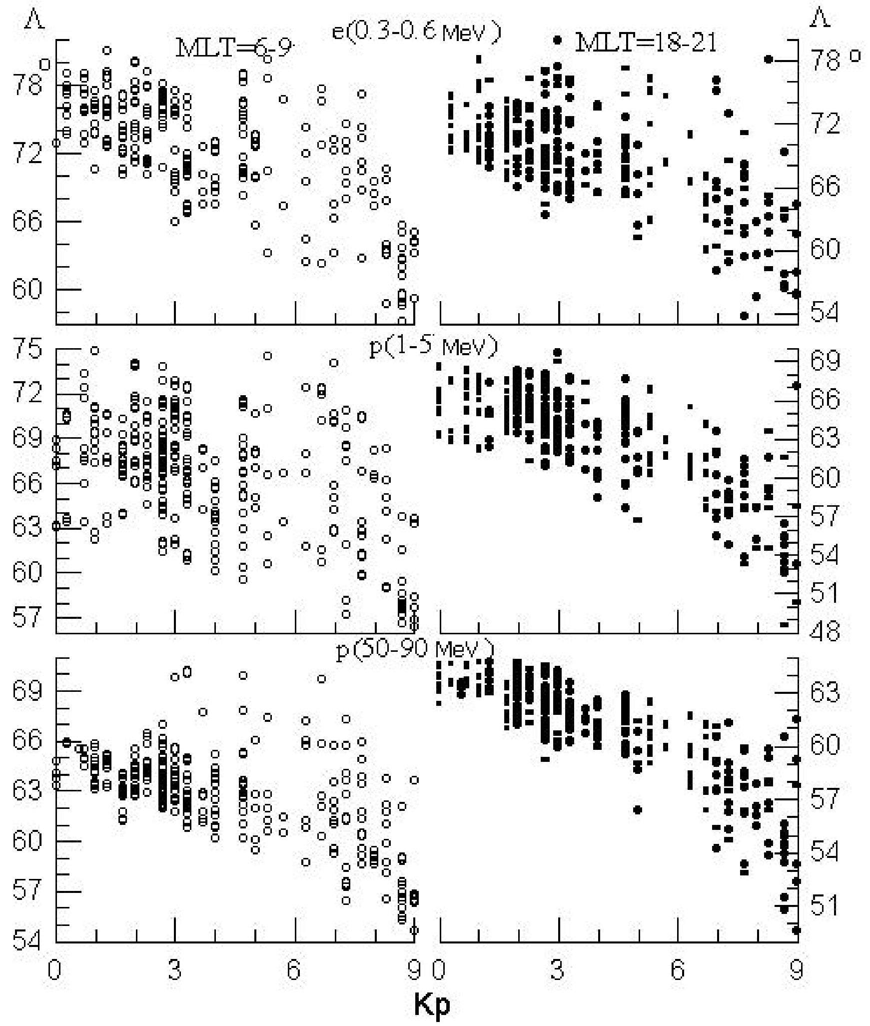

Figure 3.5. (from Kuznetsov, 2007). Position of the instantaneous boundary of solar cosmic ray penetration to the magnetosphere as a dependence on Kp index. K index is a measure of disturbance in the horizontal component of magnetic field with integer range 0-9, derived from maximum fluctuations of horizontal components observed on individual magnetometer during a three-hour interval. Kp (planetary) index is calculated as a weighted average of K-indices from magnetometer network. It can be found at http://wdc.kugi.kyoto-u.ac.jp/kp/index.html and covers the interval since 1932. .

For cosmic rays the only possibility how to check the changes of transmissivity through the magnetosphere is trajectory tracing in the magnetic field model. Different field models including external current systems have shown that the transmissivity is expected to be different for middle and low latitude neutron monitors during strong geomagnetic storms [Kudela et al., 2008].

3.4. Auroras at Middle Latitudes

Appearance of aurora at middle latitudes is one of the most significant consequences of geomagnetic storms. According to data about aurora observed long time ago it is possible to reconstruct the dates of strong magnetic storms and increased solar activity over long time period (e.g. Křivský and Pejml, 1988).

In Middle Ages the auroras were treated as precursors for various tragedies; they invoke panic fear and were considered as „prophets“ of catastrophes as wars, epidemies, hunger etc. The flashes of aurora during geomagnetic storms have been observed before the fall of Jerusalem, before death of Julius Caesar. In the history there are reported much more events of when people treated the auroras as precursors of different phenomena related to the people.

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4. GEOMAGNETIC STORMS. DYNAMICS OF RADIATION BELTS

Energetic particles of radiation belts do not affect the active processes in the magnetosphere, however, they respond, sometimes strongly, to the reconfiguration of magnetosphere. Although hundreds of papers published until now were devoted to the processes of acceleration, losses and transport of energetic charged particles in the magnetosphere during the geomagnetic storms, the complete, affirmative, unified answers on the complex processes controlling the energetic charged population during the storms, is to our opinion, still absent. The problem is not that there are unknown physical mechanisms of these processes – they are known and examined both theoretically and according to computer simulations, however, they are numerous and it is not well established yet which of them are more efficient than the others. In addition, the problem is in the fact that the magnetic storms have individual features deduced from observations and the characteristics of fluxes are different from one another.

The enhanced interest to this subject is related also to the potential applications – large fluxes of energetic protons and electrons may cause the failures of electronic systems on satellites and on other technological systems. To no end the name "electrons-killers" is used in papers of recent years, since several satellite losses/failures are caused most probably by them (for example [Baker et al., 1998]).

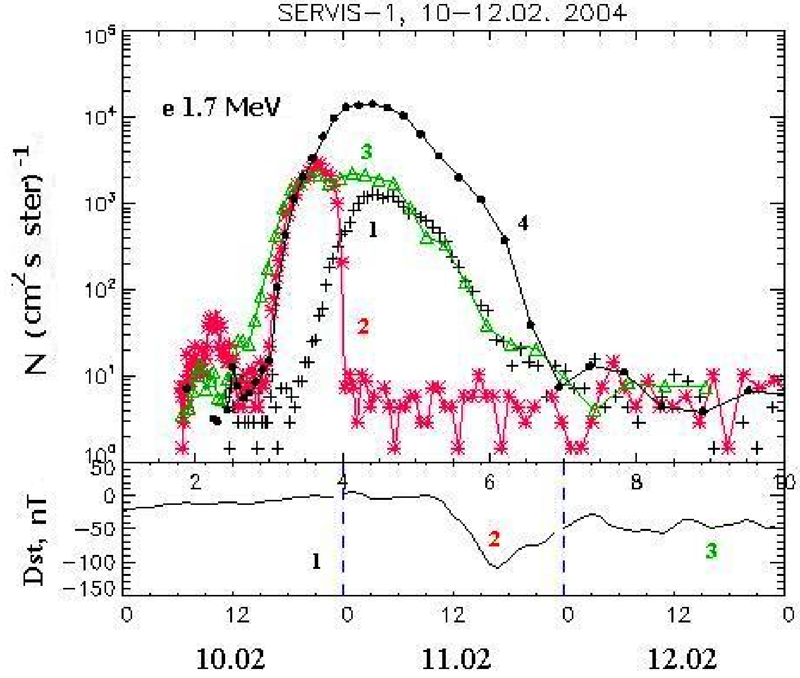

Figure 4.1. Four radial profiles of the energetic electron flux observed on Japanese low altitude (~1000 km) polar orbiting satellite SERVIS-1.

Large difference between profiles 1 and 2 is typical for all magnetic storms and decrease of counting rate of the detector in radiation belt might be explained either by the electron losses at the magnetopause or in the atmosphere or particles can move by diffusion to other drift L shells due to reconfiguration of the magnetospheric magnetic field.

The shift towards the Earth, more exactly to lower latitudes, is seen especially for minimum Dst. There is clearly seen the difference in evolution of the electron flux at L=4 and at L=3.5. For the first shell the Dst depression lead to large losses of electrons when Dst is depressed, while at L=3.5 the huge increase up to two orders is observed during the same time period. During recovery phase electron flux is subsequently increasing at L=4 and after the storm it is exceeding the flux in wide energy of Ls, especially in the outer belt.

Before we discuss in more details the dynamics of the radiation belts in general, let us describe mechanisms of particle transport, acceleration and losses acting in the magnetosphere.

4.1. Changes in Radiation Belts: Transport, Acceleration and Losses

The variability of the flux of energetic charged particles observed by detector sensitive to specific energy range on the satellites in the belts can be connected either with the real loss or acceleration of particle, however, it may be caused also with the shift of of the drift shells [Shprits et al., 2008,2008a; Friedel et al., 2002].

Adiabatic effects are caused via the reconfiguration of the geomagnetic field, which is changing particle trajectories in radiation belts with the conservation of adiabatic invariants. Classical example serves so called Dst – effect [McIlwain, 1966]. Main phase of the storms usually evolves slowly in comparison with the period of magnetic azimuthal drift of particles. In such case all the three adiabatic invariants are conserved. The third invariant is equivalent to the magnetic flux through the closed surface encompassing the drift orbit of guiding centers. Its conservation during the decrease of magnetic field strength leads to the widening of the surface which means that the drift orbit of the particle is moving away from the Earth. Since this can mean the transition of the guiding center to another field line, conservation of the second adiabatic invariant (measure of the distance between two opposite mirror points) leads to the fact that the mirror points are moving upward along the field line to higher altitude. At higher altitudes the magnetic field strength is lower, and thus for conservation of the first invariant the energy of particle must decrease. Low altitude satellite due to Dst – effect in such situation observes lower flux of particles, because the energy of "original" particle is decreasing and because the original particles due to enhancement of mirror point altitude are going out from the acceptance energy interval of the detector. During the recovery phase there takes place a reverse process in terms of adiabaticity conservation – particles have to recover their original energy and the detector observes similar type of radial profile of the particle flux.

Local adiabatic processes. If the geomagnetic field is varying sufficiently fast, the third adiabatic invariant is not conserved. When the drift shells are not closed, the third invariant is absent according to its definition. The region of maximum flux of electron belt really rather quickly becomes to be the zone of quasi-trapping. However, in such cases there may be conserved first two invariants. The example of adiabatic variations at geostationary orbit is behavior of particles during substorms in the nigh time sector of local time. During the growth phase the magnetic field here is slowly decreasing, and particles drifting in the region of equator are shifted closer to Earth along the line of equal magnetic field strength. Actually the whole slope of radiation belt profile is shifted earthward (in equatorial plane) and the counting rate on geostationary orbit is decreasing, while later during dipolization in the time of active phase of the substorm, it is recovering.

Analogical process is observed during the main phase of magnetic storm in the evening sector of auroral magnetosphere, where the partial ring current is causing local decreases of magnetic field force. Field lines with the bases were projected in the maximum of outer radiation belt, are stretched and closed in the geomagnetic tail, while drift orbits of particles are shifted to lower latitudes. Such type of stretching does not happen on the morning side, which leads to the dawn-dusk asymmetry of radiation belt.

Acceleration mechanisms. For acceleration of charged particles there is necessary electric field. Assuming the cyclic character of the particle motion in magnetosphere, the electric field can be also of variable character, especially if its frequency component is identical with the frequency of the cyclic motion of particles.

Most frequently is the acceleration of electrons in the magnetosphere examined for the case of its interaction with VLF waves in the frequency range several kHz, in the cyclotron resonance. During geomagnetic disturbances the level of VLF whistlers or chorus emissions is very high and many authors consider the interactions with waves as the source of supplying, or depletion of radiation belt population.

In the case of potential field the acceleration may be caused by the field aligned potential oscillation along the magnetic field line, however, in such case the yield of energy is not large, it is just few keV. It is not very suitable for energetic particles of radiation belt. The acceleration in the large scale convective field has to work with the magnetic drift. The electric potential east-west can reach during the geomagnetic storms the values of the order of hundreds kV, which efficiently accelerates particles and causes its motion earthward by the ExB drift.

Radial transport or injection can occur both in the single pulse of action of electric field ExB (e.g. SC impulse) as well as in the multiple action of not very strong impulses, which is denoted as radial diffusion. Formation of radiation belts is connected with radial diffusion; its velocity is

$V=1.5\ 10^{-7}\ L^{9}$ Re/day [Tverskoy, 1965]. During geomagnetic storm the substorm activity is high and the chain of substorm impulses of activation or pulsations can cause more fast radial diffusion.

Radial diffusion is observed also during the resonance interactions of a particle with geomagnetic pulsations of the types Pc3-Pc5. When the period of magnetic field variation coincides with the drift period of charged particle or with its higher harmonic, particle undergoes the action of electric field which is transporting the particle to a deeper magnetic drift shell. Since in the disturbed magnetosphere there are observed geomagnetic field pulsations in rather wide interval of frequencies, the particular shifts may be oriented towards the Earth as well as in the opposite direction, however in the sum the motion to the Earth is prevailing. Such type of acceleration by the mixture of waves is called stochastic.

Loss mechanisms. Decreases of flux of particles in the belts may be caused by three reasons: energy losses in consequence of adiabatic cooling, real loss of particle in the atmosphere, or due to its transport by the drift from the trapping region into interplanetary space.

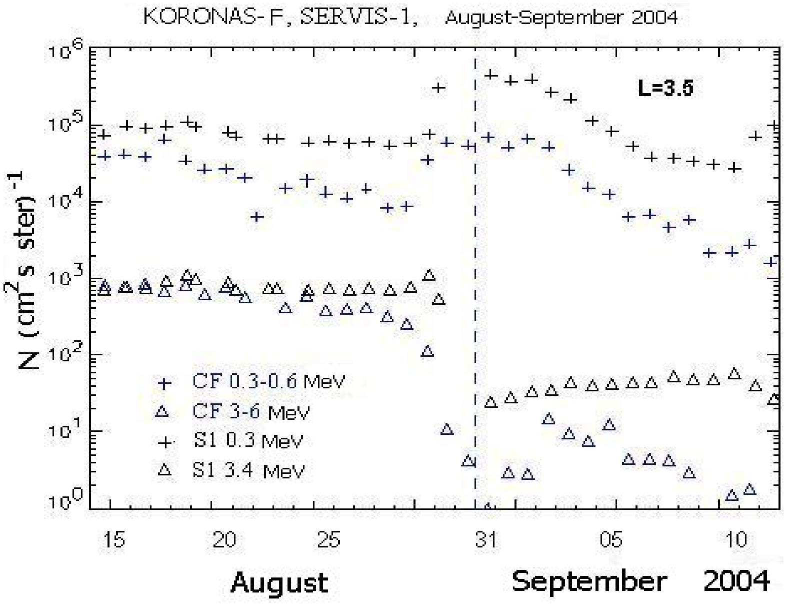

Figure 4.2. Different behavior of electrons at L=3.5 in late August and early September 2004 around the interval with moderate geomagnetic activity, as observed at two different altitudes (CORONAS-F at ~ 500 km, while SERVIS-1 at ~ 1000 km). From [Lazutin et al., 2010].

Pitch-angle diffusion is observed with the same VLF waves, which can act as a source of energy addition to the particle. For the particle to precipitate into the atmosphere, it is necessary to change its pitch-angle: at large pitch angles the particles remain trapped, however when the local pitch angle is decreasing to low values, the particle is not "finding" its mirror point above the atmosphere and it is found in the loss cone. Particle is gradually changing its pitch-angle, its wandering in pitch-angle space is similar to brownian motion, and earlier or later it falls into loss cone and it is lost.

An interesting example is the loosening of particles on ion-cyclotron waves generated by the enhanced flux of ring current protons during geomagnetic storm (EMIC waves). Since the frequency of ion cyclotron waves is much lower than the cyclotron frequency of electrons, for the resonance it is necessary to have large parallel velocity, to enhance the frequency due to Doppler effect. Requirement of large parallel velocity is putting a limit on the electron energy from beneath at level of 2-4 MeV. Figure 4.2 illustrates the example of loosening of electrons observed at energy above 3 MeV onboard the satellites CORONAS-F and SERVIS-1 during a moderate geomagnetic storm occuring on August 30, 2004. It is interesting to note that in the channel 6.6 MeV the loosening is not seen – the resonance takes place, but not in the vicinity of loss cone.

Pitch-angle diffusion of protons by their interaction with electromagnetic waves, is less intense than of electrons since the amplitudes of waves at ion-cyclotron frequency is much lower. The exception are EMIC waves observed during the geomagnetic storms. However, the gyroradius of protons is much larger than of electrons, and that is why at the outer drift shells there is a problem with their maintenance. When cyclotron radius becomes equal to about one tenth of field line curvature, pitch angle of proton is changing during each crossing the equator, which leads to the pitch-angle diffusion. Solar protons penetrating into magnetosphere undergo pitch-angle diffusion in the quasitrapping region, allowing thus to examine their dynamics with help of low altitude satellites according to fluxes of precipitating protons.

Outgoing from the magnetosphere. Reconfiguration of magnetosphere during the storm can lead to the effect when particle (both electrons and protons) go out from the quasitrapping region, i.e. they do not accomplish full magnetic drift along the closed trajectory. This leads to the loss of particles at magnetopause and/or to their exit into interplanetary space.

4.2. Influence of Storms on Radiation Belts

Therefore there are several mechanisms of losses and several mechanisms of particle acceleration. And the result of geomagnetic storm on spatial and energetic distribution of radiation belt particles (in the case of electrons the outer belt) depends on combination of these assorted mechanisms in the case of each particular storm. There exist many attempts to determine, to estimate such combination theoretically (based on the experimental data on electromagnetic radiation, geomagnetic field models etc.). There were provided numerous computational works. However, there still exist differences in the interpretation of measurements.

4.3. Trapping and Acceleration of Solar Cosmic Rays (SCR)

During magnetic storms the fluxes of SCR may penetrate into magnetosphere to low values of L as L=2.5. In favorable conditions a part of protons and of alpha particles can be trapped on the closed drift shells and supply the proton radiation belt.

There are two mechanisms of SCR trapping, both physically possible, and measured in the experiment, however they have different significance for the final status of radiation belt.

First mechanism of fast radial transport is invoked by the SC impulse: with the help of induction electric field, by the radial ExB drift, both electrons and protons occur at the inner drift shells, while due to conservation of magnetic momentum they increase the energy. Classical event of that type was observed by satellite CRRES during SC on March 24, 1991 [Blake et al., 1993].

This mechanism is attractive for clarification of the events with enhanced flux of protons in radiation belt after a number of substorms [Lazutin and Kuznetsov, 2008].

Second mechanism of SCR trapping during relaxation of magnetic field works continuously in recovery phase of the storm. For large storms the boundary of SCR penetration is shifting towards the Earth (to lower latitudes) reaching even the inner proton radiation belt.

How the protons behave during recoil of the boundary from Earth, do they remain in the trapping region or they are recoiled along with the boundary of penetration – question to which the reply depends on particle energy, rate of the change of magnetic field and on geometry and force of electric field. At L=3 the drift period of 1 MeV protons is about 15 min, while for 10 MeV and 50 MeV it is 100 s and 20 s respectively. Characteristic time of magnetic field recovery is about 10 minutes or more. In such a way, protons with the energy above 10 MeV undoubtedly conserve the third adiabatic invariant, however its conservation is not probable for lower energies. It means that protons > 10 MeV (or > 20 MeV – for different storms the different threshold energies) during their magnetic drift from the input to output from the magnetosphere are practically moving in the unchanging magnetosphere, tracking the instantaneous boundary of penetration. Protons with energy 1 MeV, drifting in the changing magnetosphere, udergo the action of the induction electric field, keeping them at the drift shells passing from open to closed ones. The same protons of 1 MeV which just enter the magnetosphere, are following new boundary of penetration. In such a manner it is created the double structure boundary observed by CORONAS-F during the strong storm close to the end of October 2003 (Figure 4.3.) [Lazutin et al., 2007].

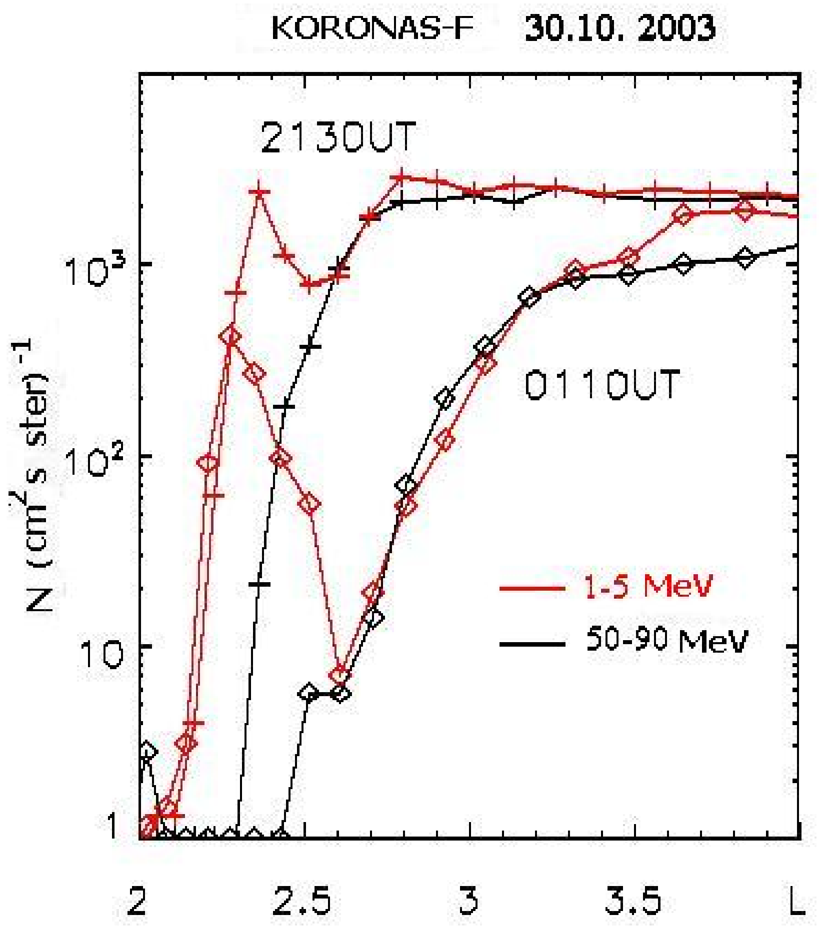

Figure 4.3. CORONAS-F indicates the double trapping boundary of SCR penetration, protons 1-5 MeV, during the magnetic storm recovery phase, October 30-31, 2003 [Lazutin et al, 2009].

In Figure 4.3 there are four L-profiles, two of them for 1-5 MeV, two others for 50-90 MeV, representing the instantaneous boundary of penetration. During the storms of September 2003 the trapping of protons was observed after the second one on September 29 as an additional belt.

4.4. RELAXATION

Electrons. As a result of acceleration mechanisms after several moderate storms and after all strong storms, in the outer belt and in the trough between the belts there were observed for rather long time the enhanced electron fluxes [Lazutin et al., 2011].

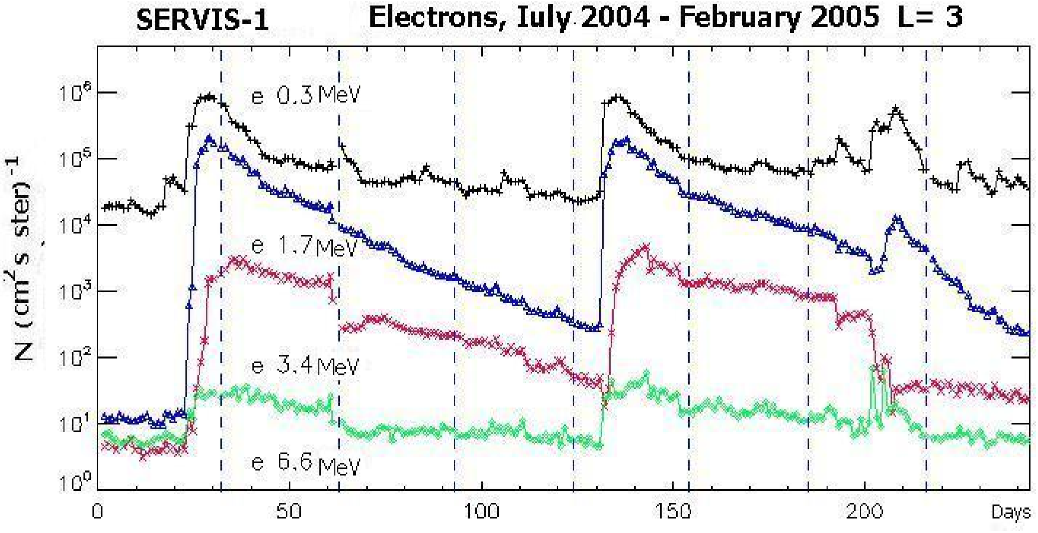

Figure 4.4. Time profile of energetic electron relaxation at L=3.

As one can see from Fig 4-4 the electron fluxes at L=3, enhanced after the three storms, remain at high level for rather long time interval and decay slowly.

Very strong increase was observed during and after the storm on July 22, 2004 at L=3, in the trough, especially at 1.7 and 0.3 MeV. For the first energy range the increase is by four orders. It is understandable that excessive flux with the time has to resume to the quiet time level. In the quiet magnetosphere the balance between supply and losses has to be established. However, the relaxation arises not suddenly, the necessary work for the release of particles into atmosphere is done by pitch-angle diffusion into loss cone by the interaction of particles with VLF waves.

While at L=3 during the 3.5 months between storms in July and November only in the energy channel 6.6 MeV the electron flux dropped to the quiet time level, in other channels it remained enhanced. At L=4 the electron precipitation goes on faster, however in channels 1.7 and 0.3 MeV there are still appearing additional increases. Both effects, more fast decay as well as increases, are connected with substorm activity – acceleration of electrons during substorms and pitch-angle diffusion into the loss cone at the enhanced level of VLF whistlers and choruses. Relation with geomagnetic activity is seen in comparison of variation of electron flux with time profile of Kp index.

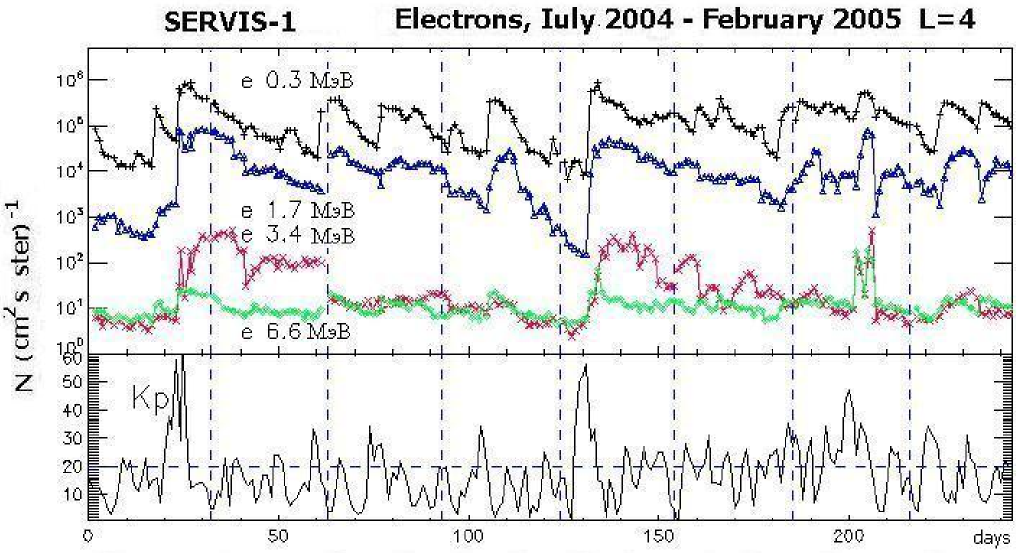

Figure 4.5. Time profile of energetic electron relaxation at L=4.

Protons. Fluxes of protons trapped and accelerated in the magnetosphere of Earth, are much more stable than the electron fluxes. Theory, developed by B. A. Tverskoy [1965], claims that proton belt is stable and that mainly the losses on ionization in the residual atmosphere decrease its fluxes with the lifetime of the order of year. There was presented suggestions that fluxes of protons of MeV energies can stably exist without significant decrease of intensity by months and years at L=2-4 shells of the radiation belt. These suggestions are confirmed only for the innermost drift shells. The belt at L=2 after injection on October 30, 2003 existed at least until the December 2006 [Lazutin, 2010], and it was once additionally supplied during the the storm in November 2004. The time profiles of lower and higher energy protons are shown in Figures 4.6 and 4.7.

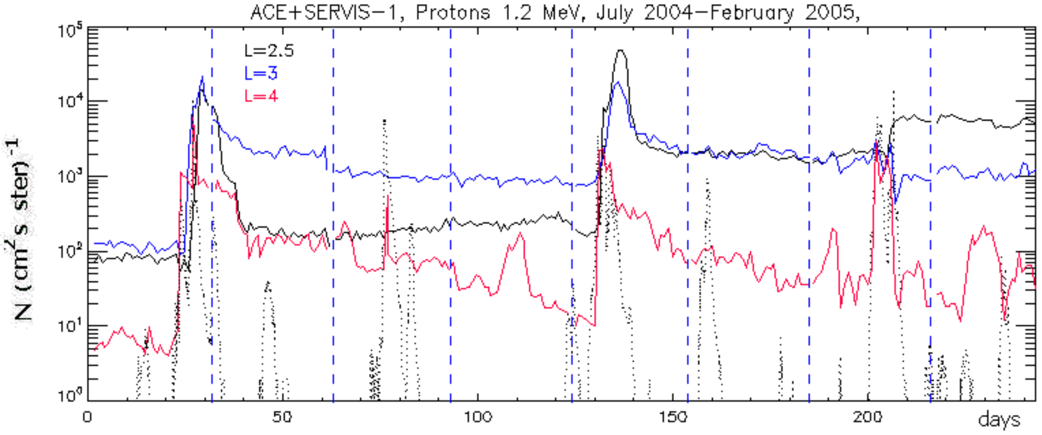

Figure 4.6. Time profile of proton (1.2 MeV) relaxation at various L shells. Protons of 1.2 MeV observed by SERVIS-1 once per day over South Atlantic Anomaly. It is seen that during the two strong storms protons of SCR penetrate to L=3 and consequently are trapped and accelerated. Dotted line depicts 1 MeV proton measurements at ACE outside the magnetosphere.

The decay of protons 1.2 MeV is observed at outer shells, at L=3 it is rather weak, and at L=2.5 the observed increase is apparently due to radial diffusion. Comparison with measurements at L=4 indicates that protons of SCR penetrate here not only during the strong storms, but also in connection with moderate storms December 5-6, 2004; January 17-21, 2005 and also during the substorm activity September 14, 2004. However, these particles do not supply the stable trapping populations. Storm in January 2005 is causing increase of proton flux even at L=2.5. Short time increases at outer drift shells, not connected with the increase of flux out of the magnetosphere, are observed during moderate and even during weak storms.

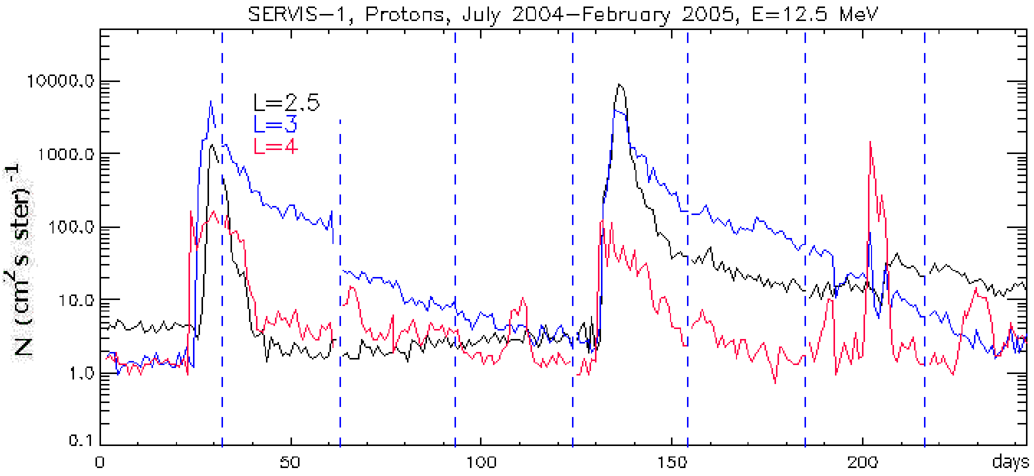

Figure 4.7. Time profile of proton relaxation (12.5 MeV) at different L shells during the period July 2004 – February 2005 as observed on SERVIS-1 satellite.

The decay of the proton flux 12.5 MeV, increased during penetration of SCR protons into magnetosphere, is faster than that for low energies. The decay is slightly slower after the storm in November 2004 than that after July 2004.

For the supply of proton belt by the SCRs it is necessary, that during strong magnetic storms, let us say at Dst < -250 nT, around the Earth it is occurring large flux of SCR. Such interconnection is not rare. Figure 4.8 is illustrating that [Lazutin and Logachev, 2009]. Position of the points corresponds to the time and intensity of the magnetic storms and color of the points divide them by the intensity of the accompanied SCR protons. Solid line indicates development of the solar cycles.

It is seen that they are concentrated at the declining phase of the cycles. If we assume that each of the event of trapping of SCR is creating increase of proton flux in the belt lasting about a year, it means that approximately half of the total time the proton radiation belt is built up by SCR, and during the other half the traditional mechanism of belt formation by the slow radial drift of auroral protons, is significant. This, of course, is valid for the low energy proton radiation belt. The trapped protons above approximately 20 MeV is not affected by geomagnetic storms and it is created in the inner zone mainly by the CRAND mechanism (cosmic ray albedo neutron decay), which is out of the scope of this chapter.

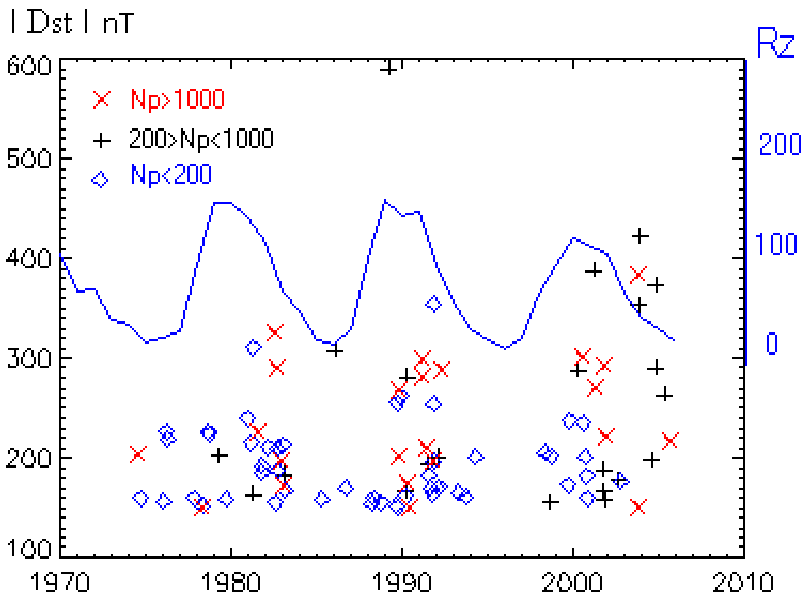

Figure 4.8. For three last solar cycles there are marked times of strong magnetic storms, accompanied by enhanced flux of protons. Np is a maximal 10 MeV proton flux in cm^{-2} s^{-1} ster^{-1}.

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