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Relaxation of Electron and Proton Radiation Belts of the Earth after Strong Magnetic Storms

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Abstract—During strong magnetic storms in July and November of 2004 the fluxes of trapped particles (protons and electrons of MeV energies) in the Earth's radiation belts have increased by orders of magnitude and then decreased remaining on an enhanced level for several months. These enhancements allowed us to study the processes of relaxation of the radiation belts. Measurements of energetic particles by low-altitude satellites *Coronas-F* and *Servis-1* have shown that predictions of the theory about the rate of pitch-angle diffusion are not always correct, giving both overestimated and underestimated values for the lifetime of energetic particles.

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1. INTRODUCTION

Since the moment of discovery of the Earth's radiation belts the long-term variations of particle fluxes in the belts were studied both in theoretical and in experimental works, and mechanisms of these variations are generally understandable. On the outer drift shells significant changes in the fluxes of energetic electrons and protons are caused by magnetic substorms and moderate storms, while strong magnetic storms produce effects on the inner shells. The disturbed fluxes of particles gradually decrease due to pitch-angle diffusion into the loss cone, carryover onto the magnetopause, and (on the inner shells) due to ionization losses. The theory of pitch-angle diffusion was developed in 1970s and 1980s [1, 2]. Active experiments with artificial injection of charged particles have allowed the process of diffusion on the inner shells to be studied and main points of the theory to be confirmed. On the outer shells, measurements on geosynchronous satellites give valuable experimental material. Here, together with losses, an increase of particle intensity is also observed due to acceleration by waves, and radial diffusion in large-scale and local variable electric fields.

On the inner shells the processes of replenishment and losses of particles are balanced, and, though proportions of these processes are theoretically understandable, it is difficult to confirm experimentally the results of modeling and to separate these processes. During strong magnetic storms the structure of the radiation belts changes radically. Losses of particles prevail on the main phase, while on the recovery phase the acceleration of both protons and electrons takes place, the gap between the electron belts disappears, additional maxima emerge, and the intensity increases by several orders of magnitude. Return to the normal structure proceeds slowly (over months) and has a complex character, several mechanisms of pitch-angle diffusion being in competition with acceleration processes (see reviews [3, 4] and references therein). Theoretically these processes were studied in great detail, but the number of experimental works confirming predictions of theory is small.

A series of strong magnetic storms in October–November of 2003, and in July and November of 2004 allowed us to investigate in detail the processes occurring in the belts during strong storms using measurements of low-orbit satellites *Coronas-F (CF)* and *Servis-1 (S1)* [5–8]. In this paper the rate of relaxation of particles after storms is studies as a function of energy, drift shell (L), and time after the storm. Obtained results are compared to predictions of model calculations.

2. MEASUREMENTS

Both the satellites (*CF* and *S1*) had polar orbits with heights of 500 and 1000 km, respectively. Both were equipped with spectrometers of charged particles, allowing one to measure in several channels the fluxes of electrons (with energy from 0.3 up to 7 MeV) and protons (from 1 to 50 MeV). In the majority of orbits the fluxes of precipitating particles were measured, and only during passages over the South Atlantic Anomaly (SAA) spurs of the radiation belts were crossed. To study the dynamics of particle fluxes at chosen drift shells, the program selected the maximum

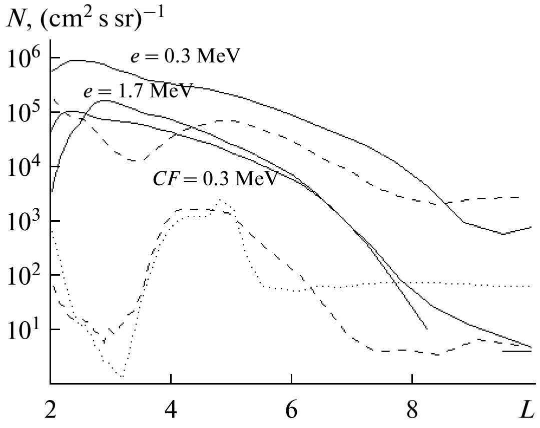

Fig. 1

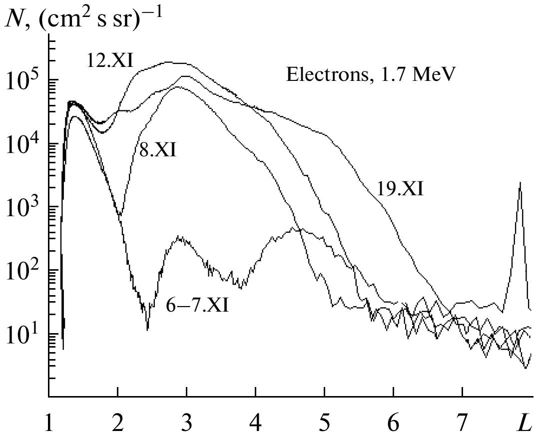

Fig. 2

value of intensity every day: this value was reached during one of passages over the SAA. A detailed description of the instrumentation is given in [9, 10].

2.1. Relaxation of the Fluxes of Electrons

Figure 1 presents the radial (according to L-shells) profiles of electrons before (dashed lines) and after (solid lines) a strong magnetic storm on July 22–28, 2004 in two energy channels of *S1* and in a single channel of *CF*. Before the magnetic storm a standard profile is detected with a maximum of the outer belt at $L = 4$–6 and a dip between the belts in the region $L = 3$. After the storm the intensity of electrons increases at all L-shells up to the auroral zone inclusive, the dip disappears being filled by electrons, and the growth of electron intensity in the channel 1.7 MeV at $L = 3$ exceeds four orders of magnitude.

The flux of electrons recorded by *CF* is an order of magnitude lower than that on *S1*, which corresponds to distribution of the particle flux along a field line. When studying the long-term variations one finds that the particle flux on *CF* decays more rapidly due to transformation of the pitch-angular distribution to the side of increasing pitch-angle anisotropy, and a false impression is produced that the excess flux of trapped particles has disappeared. Therefore, in this paper we use more frequently the *S1* data. But even for them one should have in mind that the particle losses due to diffusion in the equator plane can proceed slower than near the loss cone at the satellite altitude. Consequently, the presented below lifetime values for particles can be a bit underestimated.

Figure 2 shows the transformation of radial profiles of electrons (satellite S1) during the magnetic storm on November 7–11, 2004 that consisted of two storms. In this case the data of one channel is presented (electrons with energy of 1.7 MeV), however, the profile variations are shown not only in the storm's beginning and end, but during the storm as well. In the initial (pre-storm) profile in addition to the usual maximum at $L = 4.5$ one can see a maximum at $L = 2.8$, where the enhanced particle flux still survived after the July magnetic storm. The second profile falls on the recovery phase of the first storm, and the third profile corresponds to the recovery phase after a new jump of the ring current on November 11. Here, we observe an increased intensity of electrons in a wide range of drift shells. The recovery phase has dragged out until November 20, and at this stage we observe continued increase of electron intensity on outer shells, while on the inner shells ($L \sim 2$–4) a drop of intensity begins which continues after the storm too.

Such are the original fluxes of electrons having increased during two magnetic storms, after which a relaxation to the normal state on the radiation belts begins.

Figure 3a and 3b present the time behavior of electron intensity in four energy channels at $L = 2.5$ and 3 during passages over the SAA. The maximum counting rate is presented for every day since July 2004 until February 2005 inclusive. In the process of recovery of the radiation belt to its quiet level, as a rule, one can isolate two stages: the initial stage, immediately after filling the belt during the July and November storms, is a fast drop, which is followed by a long relaxation with large lifetimes. In some cases the initial, more rapid decay is better described by an exponent $N(t) = N_0\exp(\gamma t)$, but in the majority of cases the decay character is described by a power law form , where $1/\gamma$ is the characteristic time (lifetime) in which the intensity drops down by a factor of e.

Figure 4 presents a similar plot for the drift shell $L = 4$. Here, fast and short-term variations (related to both increases and decreases of intensity, with a char-

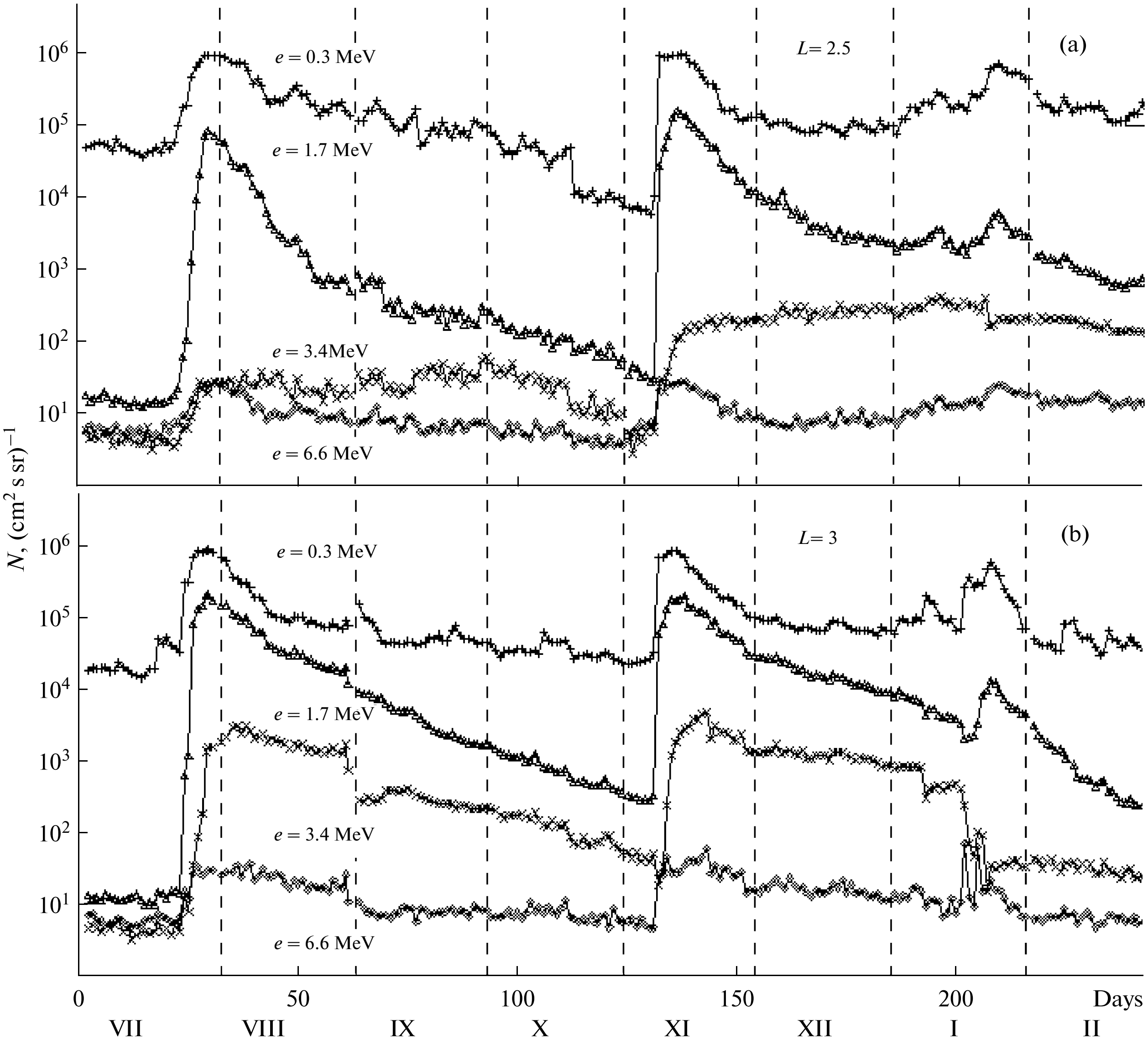

Fig. 3

acteristic time of a few days) are superimposed on the slow decrease of the intensity.

The short-term variations increase with the distance from the Earth and with decreasing energy of electrons, which definitely indicate to their connection with the auroral activity. The same follows from a comparison with the time behavior of K_p index of magnetic activity shown in the bottom panel of Fig. 4. This type of variations is fairly well described in the literature, especially as far as measurements on geosynchronous satellites are confirmed, and we do not consider them here.

The partition of relaxation process in two stages is observed in channels 0.3 and 1.7 MeV at $L = 2–3.5$, while in more energetic channels and at $L = 4$ this partition is worse pronounced.

Some deviations from a regular decay of intensity took place in January 2005, when three magnetic storms were observed. In channel 3.4 MeV at $L = 2.5$ the enhanced flux persisted for a long time both after the first and after the second storm, while at $L = 3$ a stable decay is seen, which, however, does not reach the quiet level for all 6 months of measurements. In channel 6.6 MeV the enhanced counting rate is observed during 1–2 months after the storm. It should also be noted that short-time enhancements in January 2005 at $L = 3$ and 4 are due to penetration of solar electrons into the magnetosphere.

One more type of fast variations is observed during moderate magnetic storms. In the interval under study it was observed on August 30–31, 2004 and January 17–21, 2005. The increase of intensity in two channels 0.3–

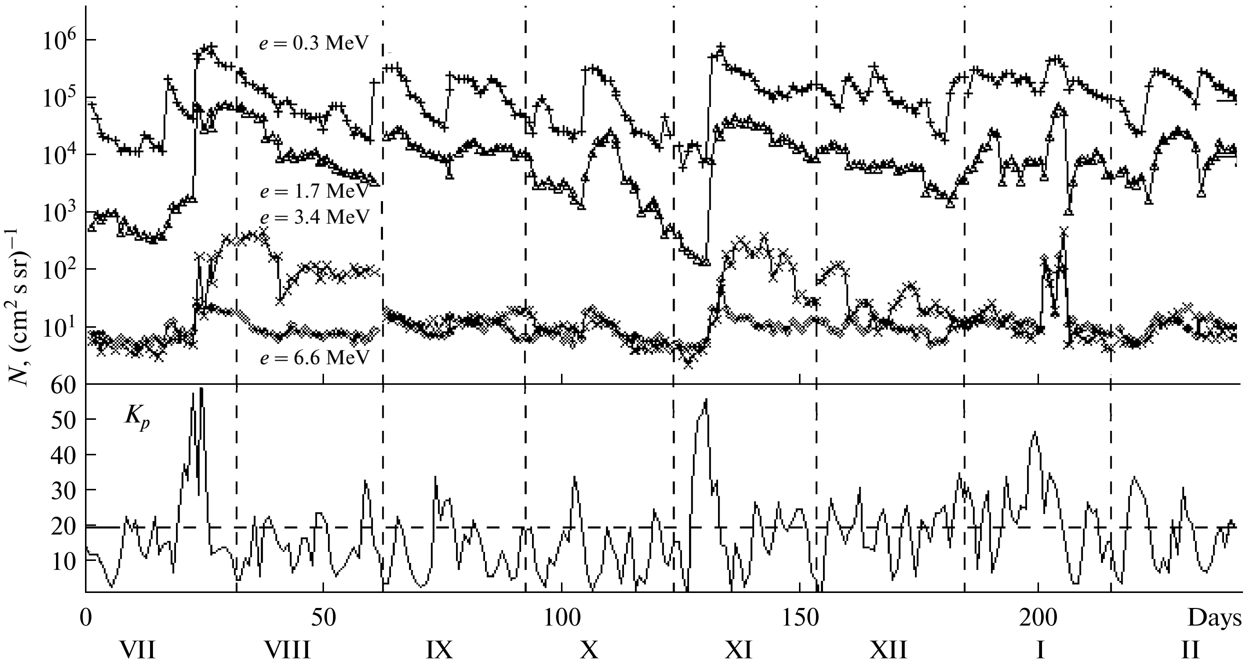

Fig. 4

1.7 MeV caused by intensification of wave activity is accompanied by a considerable drop of intensity in channel 3.4 MeV.

This effect is produced by ion-cyclotron waves generated by protons of the radiation belt (EMIC-waves). Dynamics of particles during the August storm was studied in detail in paper [11].

Figure 5 presents the time behavior in channel 1.7 MeV (satellite *S1*) for all three *L*-shells, which allows one to detect identical rate of decay during the second stage of relaxation that is seen on the background of short-time variations. Apparently, pitch-angle diffusion determining the slow decay of intensity proceeds by VLF emissions, which are close in power and distributed over a broad range of *L*-shells. The plasmaspheric hiss possesses such properties.

Thus, relaxation of electrons after a storm is divided in two stages, with fast and slow losses of trapped particles. It depends on the position of a drift shell and on energy of electrons.

Figure 6 presents the values of lifetime γ for electron flux in channels 0.3 and 1.7 MeV as a function of *L* separately for intervals after the July and November filling and restructuring, and separately for the initial and second stages of relaxation.

One can see that γ of the initial fast decay (below the dashed line) varies within the limits 5–10 days independent of energy and position of the drift orbit, while at the second stage the scatter of this quantity is much larger. One can note that the intensity drops down in channel 1.7 MeV faster than in channel 0.3 MeV, and that the fastest drop in both the channels is observed at $L = 3.5$, in the region of a gap between the belts.

2.2. Relaxation of the Flux of Protons

Enhancements of the flux of protons with energy 1–20 MeV in the proton belt are associated with capture of solar protons at the early phase of recovery of the storm and with additional acceleration at its late stage. Figure 7 presents radial profiles of protons before (July 22, 2004, dashed line) and after (July 30, 2004, solid line) the magnetic storms in July 2004, as measured on *S1* and *CF*.

It is seen that during two strong storms SCR protons penetrate down to $L = 3$, where they are captured and accelerated. The profile on August 25, 2004 measured by *S1* shows the result of capture of SCR protons after the first storm. The process of particle acceleration starts with this profiles and results in the profile of July 30. The maximum of the quiet profile is located at $L = 3$, the *CF* intensity being an order of magnitude lower than that on *S1*. The after-storm flux increased by two orders of magnitude is shifted to $L = 2.8$ as a result of radial diffusion. There is no such shift on *CF*. Apparently, only situation near the loss cone rather than the real radiation belt profile is observed here.

Figure 8 present three profiles of protons in channel 1.7 MeV of the *S1* satellite: before the onset of the November storm, in the middle of the recovery phase, and a few days later, on the tail of prolonged recovery

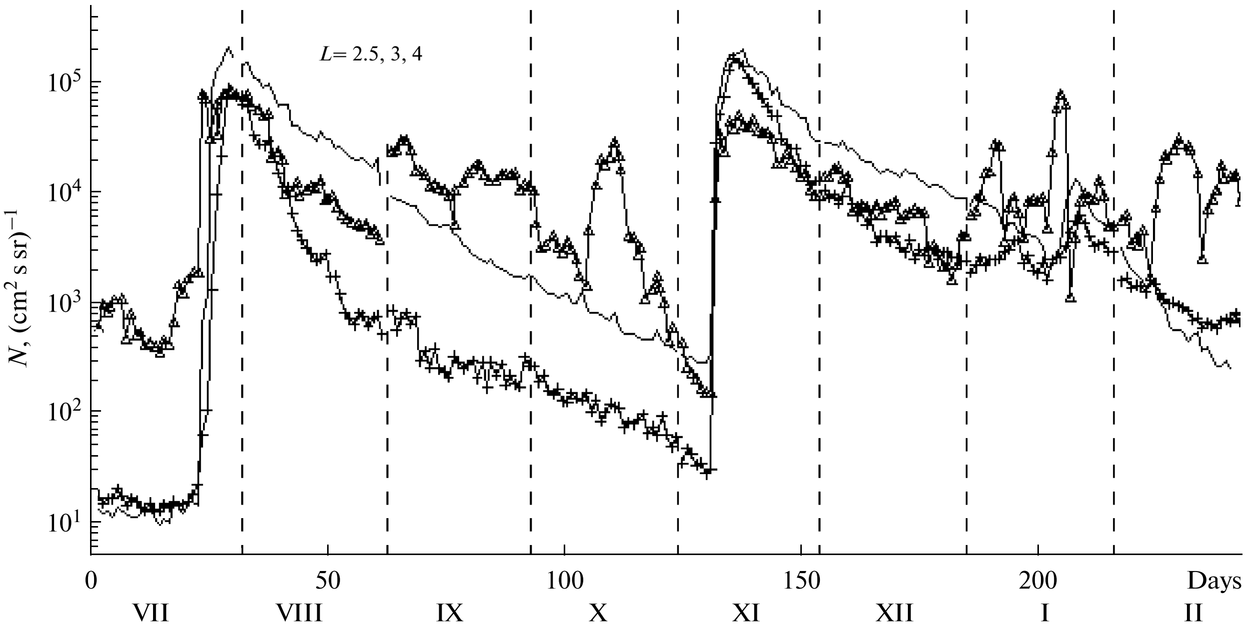

Fig. 5

phase. In the maximum at $L = 3$, before the storm onset, an enhanced intensity persists (in comparison with the quiet level on July 30, 2004, see Fig. 7). On November 12 this maximum is shifted to $L = 2.5$, the intensity increases by two orders of magnitude, and then a quick discharge of particles into the loss cone begins, resulting in the appearance of two maxima, at $L = 2$ and 3.

Variations of the flux of protons with energy 1.2 MeV are shown in Fig. 9a at $L = 2.5$, 3, and 4 from July 2004 up to February 2005 inclusive. Relaxation of the proton flux, according to measurements on low-orbit satellites, follows the same scenario, as relaxation of the electron flux described above. As in the case of electrons, one can distinguish two stages in particle losses, the fast one immediately after a magnetic storm and a subsequent slow stage. The drop proper is observed only on the outer shells, at $L = 3$ it is extremely weak, while at $L = 2.5$ an increase of the intensity is observed, apparently, due to radial diffusion.

The dashed line in Fig. 9a represents the flux of 1 MeV protons beyond the magnetosphere according to measurements made by the *ACE* satellite. Comparing these measurements with measurements at $L = 4$, we see that SCR protons penetrate there not only during two strong storms, but during moderate magnetic storms on December 5–6, 2004 and January 17–21, 2005, and even during the substorm activity on September 14, 2004. However, they are not captured into the radiation belt during these events, though the January 2005 storm increases the proton flux at $L = 2.5$. Short-period enhancements on the outer drift shells, not associated with the increased flux beyond the magnetosphere, are observed during moderate and even weak storms (–120, –50, –100, and –100 nT on August 30, 2004, October 13, 2004, January 7, 2005, and February 16–18, 2005, respectively).

Figure 9b presents the time behavior of relaxation of protons in channel 12.5 MeV of *S1*. The rate of proton loss at these energy is higher, and after the first stage of the July storm the enhanced flux remains practically only at $L = 3$. After the November storm the relaxation is more prolonged. In channel 24.6 MeV variations are insignificant, and we do not present these data.

As has been said above, it is more difficult to use measurements onboard the *CF* satellite for the analysis of slow variations of trapped particles. First, measurements made at low altitude, near the loss cone, represent variations of particle fluxes in the proton belt worse. Second, the acceptance angle of the scintillation detector slowly varies with respect to magnetic field line direction with a period of 3 months. As a result, on those days when the detector is oriented along the field line the particle flux decreases. In Fig. 10, where variation of the proton flux on *CF* are shown, two such periods fall on September and December of 2004. Comparison with *S1* (Fig. 9a) shows the distinctions to be large at the fast stage: maximum on the *CF* is prolonged, and intensity in the maximum is lower. On the slow stage of relaxation there are no distinctions, substantial losses are observed on the outer drift shells ($L = 4$), while on the inner shells the proton flux varies more slowly.

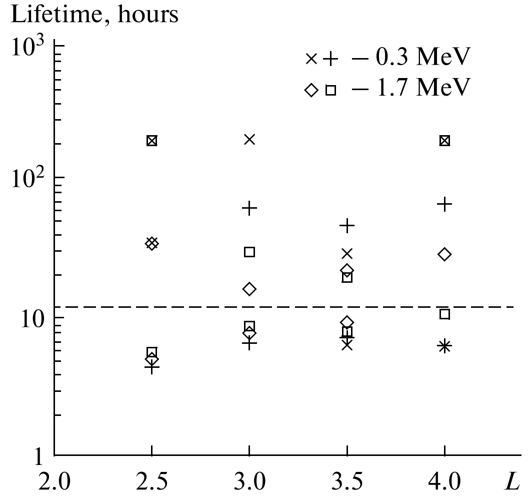

Fig. 6

A summary diagram on the lifetime of protons is presented in Fig. 11, for the same two storms, as for electrons, and for two proton energy channels, 1.2 and 12.5 MeV. For the initial, fast regime of losses, the difference in energy is insignificant. The fact of a fast drop (below the dashed line) of intensity at $L = 2.5$ engages our attention.

At the second stage the drop proceeds slower than that of electrons. Moreover, an increase of intensity is observed at $L = 2$, apparently caused by radial diffusion from neighboring outer shells. The values of γ at a level of 100 and higher are rather conventional and can imply either invariable or increasing particle flux. It is worthy of noting that with increasing energy the rate of slow losses increases. It also substantially increases when drift shells become further from the Earth.

3. DISCUSSION OF RESULTS

A large number of papers with theoretical calculations are dedicated to mechanisms of losses of electrons and protons in the radiation belts. The papers on relativistic electrons are especially numerous, since real danger of electrons-killers for space instrumentation stimulates interest to them. The most complete review on pitch-angle diffusion of electrons on various types of VLF emissions is given in paper [4] with estimation of lifetimes. A calculation of lifetime of energetic protons after injection during magnetic storms is presented in [12]. We will compare our results with predictions of losses of energetic particles calculated in these papers.

The processes leading to reduction of the flux of trapped particles in the magnetosphere are well studied. If losses on the magnetopause in the region of quasi-capture and on ionization at $L < 2.5$ are not considered, the main role is played by pitch-angle diffusion of particles. It results in entry into the loss cone and vanishing in the Earth's atmosphere. The diffusion is caused by resonance interaction of particles with electromagnetic waves at a coincidence of wave frequency with gyro frequency of a particle in the coordinate system of the moving particle

$$\omega - k_{\|}v_{\|} = n\Omega_{ep}/\gamma, \quad n = 0, \pm 1, 2, 3, \ldots, \qquad (1)$$

where ω and Ω_{ep} are the wave frequency and gyro frequency of particles, either electron or proton, $k_{\|}$ and $v_{\|}$

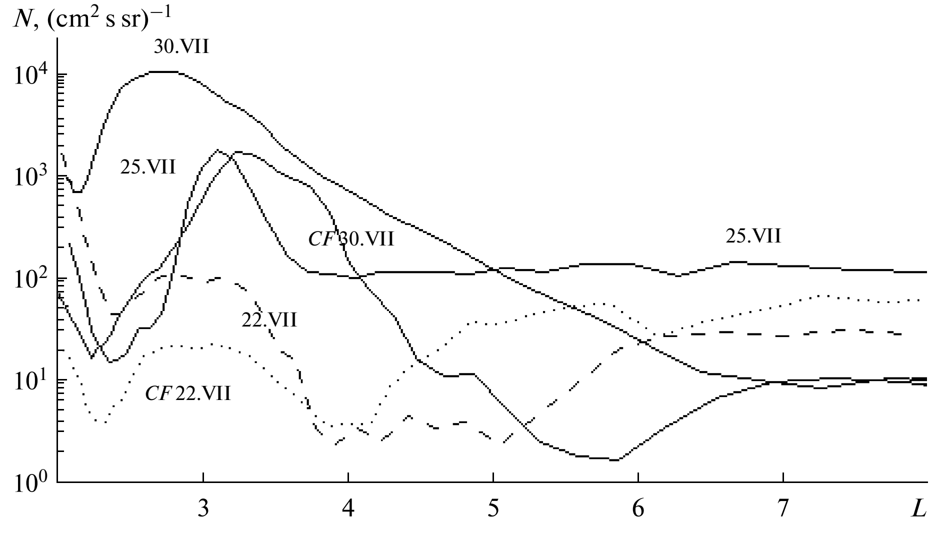

Fig. 7

are the components of wave vector and velocity of particles along the magnetic field line, and $\gamma = (1 - v^2/c^2)^{-1/2}$.

Under the assumption of constant energy and drift shell the Fokker–Planck diffusion equation for pitch-angle diffusion can be written as

$$\frac{\partial f}{\partial t} = \frac{1}{T(y)\,y}\frac{\partial}{\partial y}T(y)\,y\left\langle D_{yy}\right\rangle_{ba}\frac{\partial f}{\partial y} - \frac{f}{\tau}, \qquad (2)$$

where y is sinus of the pitch-angle, and T is a quarter of the jump period.

The lifetime of particles in a trap, defined as a time of decay of intensity by a factor of e, can be related to the diffusion coefficient as $\tau = 1/D$.

Fluxes of electrons. In the energy range 0.3–3 MeV they remain at a disturbed (enhanced) level after the July storm since July till November 2004 both on inner (L = 2–3.5) and on outer shells. The enhanced level also persists after increased intensity during November 2004 storm at least until March 2005. In channel 6.6 MeV the normal level is recovered in 1–2 months. A large number of various types of waves are detected in the Earth's magnetosphere. Some of them are distinguished as essential to make an effect on the fluxes of trapped electrons and widely discussed in experimental papers and model calculations.

In the inner magnetosphere (L = 2.5) electron can perish in interactions with whistling atmospherics produced by lightning discharges and anthropogenic VLF emissions [13], and in collisions with residual atmosphere. The lifetime of electrons is no less than a month, and there is no difference between magnetically disturbed and quiet conditions, since the action of the above sources does not depend on magnetic activity.

The measurements presented above show that in those cases when the effect of strong magnetic storms reaches regions $L < 3$, high fluxes of energetic electrons appear there, and the rates of losses of freshly accelerated relativistic electrons substantially exceed those typical for quiet and moderately disturbed conditions. The lifetime drops down to 4–6 days in channels 0.3 MeV and to 10 days in channel 1.7 MeV. This regime continues for 10–20 days after termination of the magnetic storm recovery phase. A difference in rates of the initial and subsequent drops of electron fluxes is also observed at $L = 3$, but it is not so well pronounced. Having in mind considerable enhancement of the flux of energetic electrons at L = 2–3 during strong magnetic storms, it is reasonable to explain intensified loss of electrons by generation of cyclotron waves. The lifetimes presented above coincide with estimates for losses by auroral whistlers made in paper [4]: 2 days for $E = 0.5$ MeV and 15 days for $E = 2$ MeV. However, one should not interpret this coincidence in the sense that the auroral region or even the magnetotail were located at that time at $L < 2.5$. Even if they were (which is unlikely), at the end of the storm's main phase (i.e., in a few days) all typical attributes of the inner magnetosphere had returned back, except for the fact that the flux of energetic particles remained very high.

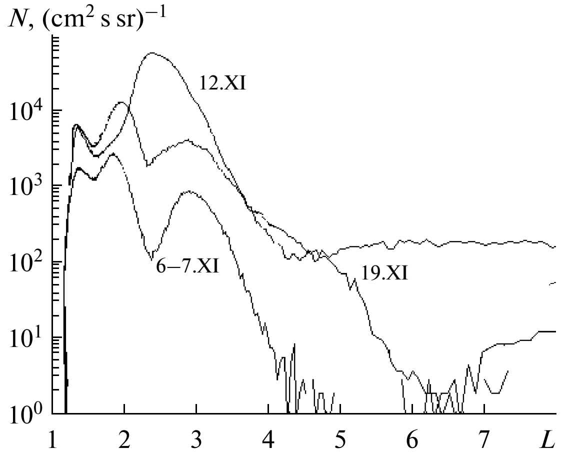

Fig. 8

Our measurements at $L = 2.5$ show that during the second stage with the slower rate of losses the lifetime of electrons 0.3–1.7 MeV is no less than 30 days, which corresponds to estimates of losses by ionization and to pitch-angle scattering by waves of anthropogenic and atmospheric origin.

At the same time, on separate days the drop of intensity is slowed down and even goes over into a growth. One can notice that at this time an enhanced substorm activity is detected or moderate magnetic storms (for example, August 30, 2004 and January 21, 2005). It is logical to explain these enhancements by impulsive radial injection of particles. A bright event of such injection by a sudden commencement (SC) in the beginning of the magnetic storm on March 24, 1991 was detected by the *CRRES* satellite [14].

It is interesting that the same enhancements are observed also at L = 4 and with larger amplitude, which is natural for the auroral zone, while at $L = 3$ the amplitude is less than on a deeper drift shell. If we attract our attention to a radial profile of electrons with two maxima at L = 3 and 4.7 presented in Fig. 2 before the November storm onset, we see that at L = 2.5 and 4 the flux gradient for particles in the belt is positive, while at $L = 3$ a transition to negative gradient occurs. In the first two positions the increase of intensity of electrons at impulsive injection is a sum of two effects: income from a region with higher intensity and acceleration due to conservation of the first adiabatic invariant. The depleted flux of particles comes to L = 3, and only increasing energy produces enhancement.

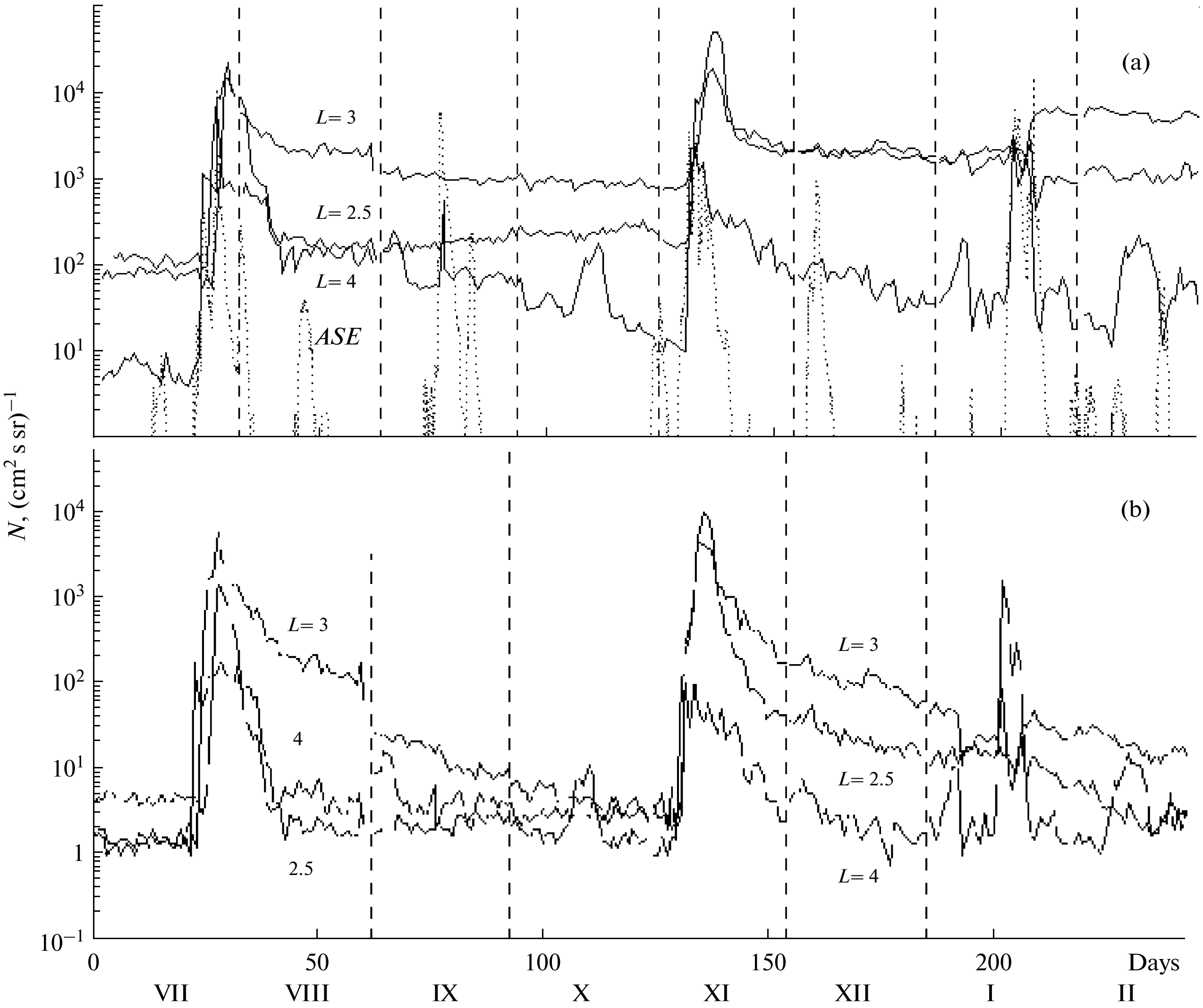

Fig. 9

As for variations at $L = 2.5$ in channels of high-energy electrons (for example, in channel 3.4 MeV), the intensity is practically invariable after enhancements, with an exception of one interval in October 2004. In channel 6.6 MeV a drop of intensity is noticeable at the first stage, and on the second stage dynamics is contradictory: there is a slow decrease after the July storm and nothing of this kind after the November storm. Probably, this is a result of increased magnetic activity in December 2004 – January 2005.

The first, fast stage of loss is much weaker pronounced at drift shells $L = 3–4$ than at $L = 2.5$. It is well traced only at $L = 3$ in channel 0.3 MeV. The second stage with a slower drop proceeds under conditions of weak or moderate activity. In this case, the plasmapause is located higher than $L = 3$, and occasionally it overlaps the drift shell $L = 4$.

Inside the plasmapause VLF emissions of the hiss type dominate, ensuring, according to estimates of [15, 16], the following lifetimes of electrons: 3 days for 0.5 MeV, 10 days for 1 MeV, and more than 40 days for 2 MeV.

It follows from analysis of our data that, first, the fluxes of electrons in channels 0.3 and 1.7 MeV vary synchronously at all drift shells (Fig. 5), thus confirming the conclusion of above authors about predominant action of the plasmaspheric hiss on electrons. The lifetime was about 30 days for 1.7 MeV and about 50 days for 3.4 MeV. Electrons with energy 0.3 MeV survive substantially longer than it follows from theoretical estimates (a few days). It is likely that an acceleration process of substorm origin comes into play, providing for intensity increases instead of fast drop at some intervals.

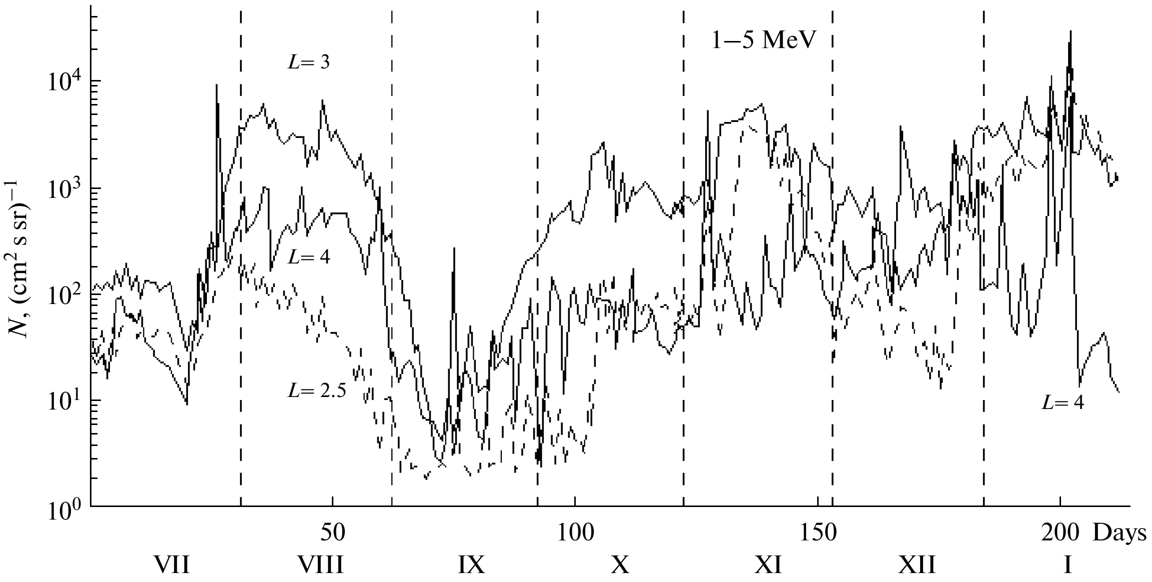

Fig. 10

The processes of acceleration of relativistic electrons are caused by radial diffusion and by stochastic processes [17]. Some researchers believe the VLF interaction with emissions of the types of auroral choruses and whistlers to be the main mechanism of acceleration and loss of electrons in disturbed periods outside the plasmasphere (see [4] and references therein). The choruses should be divided in two groups with different proportion of the effects of acceleration and losses. These fast increases and drops are well seen at $L = 4$ (Fig. 4). In channel 0.3 MeV they dominate over slow protons. The losses on whistlers are equal to 2, 5, and 15 days for energies 0.5, 1, and 2 MeV, respectively.

At energies higher than a few MeV additional and fast drop occurs due to parasitic resonance with electromagnetic ion-cyclotron waves (EMIC waves) produced by ring current protons during magnetic storms [18–20]. In our measurements the fast drops of electrons 3.4 MeV were observed on August 30, 2004 at $L = 3–4$ and during two storms of January 2005. The first of these events is considered in detail in [11]. Contrary to predictions, there is no effect of drop in channel 1.7 MeV. It is probable that effects of acceleration suppress losses by EMIC waves.

Fluxes of protons captured in the Earth's magnetosphere are much more stable than the fluxes of electrons. The theory developed by Tverskoi [1] states that the proton belt is stable, and only losses through ionization by the residual atmosphere decrease proton fluxes with a lifetime of about a year. Calculation performed in [12] were specially dedicated to the problem discussed by us: how the flux of protons in the belt will behave itself after injection of solar protons. The model predictions are such that fluxes of protons of MeV energies will be stable, persisting without noticeable reduction of intensity for months and years at all L-shells of the proton belt from 2 to 4. These predictions are not confirmed by the results obtained above.

Indeed, in the magnetosphere there are no intense electromagnetic waves on ion-cyclotron frequencies other than EMIC ion-cyclotron waves that are generated for short time intervals and not frequently by protons of the ring current. They cannot create a continuous background for losses of energetic protons. What mechanisms do remain capable to provide for a high rate of losses detected by us?

1. Losses due to diffusion on the curvature of field lines.

2. Diffusion on ion-cyclotron waves excited at enhanced intensity of energetic protons.

3. Parasitic resonance with VLF emission at electro-cyclotron frequencies.

At the stage of fast drop the losses proceed by ion-cyclotron waves. According to estimation by Tverskoi [1], the belt proton flux is by two orders of magnitude lower than it is required for development of ion-cyclotron instability; we have got these two orders of magnitude after acceleration of MeV protons during the recovery phase of strong magnetic storms in July and November of 2004. Just energetic protons rather than ring current protons (whose flux drops quickly after a storm, while a fast mode of diffusion still persists) serve as a source of waves. The proton lifetime varies from 15 days at $L = 2$ to 5 days at $L = 4$. Increasing rate of losses is clearly seen when a drift shell moves away from the Earth. It is unclear why essentially acceler-

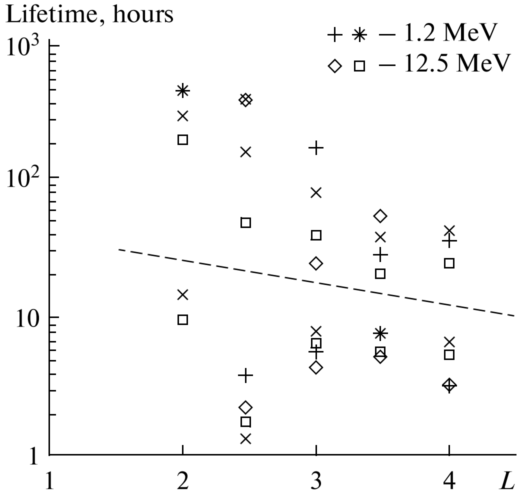

Fig. 11

ated loss occurs at $L = 2.5$. Probably, this is due to the fact that during strong storms the plasmapause (where one always can detect an increased wave activity) is displaced to these region.

At the slow stage the fluxes of protons 1–15 MeV remain at a disturbed level for a period of three moths to a year, depending on energy and drift shell position. The lifetime equals 200 days and more at $L = 2$, which corresponds to calculations in [12]. But at larger L the lifetime successively drops down to 20–40 days (at $L =$ 4), which is in evident contradiction with estimates of [12]. The drop of intensity in channel 12.5 MeV occurs approximately twice faster than in channel 1.2 MeV. The rate of losses increases when drift shells become more distant from the Earth.

These losses are compensated by radial diffusion with conservation of magnetic moment, i.e., with acceleration of protons. Indeed, in the examples presented above the effect of radial diffusion is seen at $L = 2.5$ in all energy channels. Nevertheless, the drop detected at large L-shells is much faster than one could expect based on the theory of losses due to ionization.

The mechanism of pitch-angle diffusion into the loss cone due to violation of adiabaticity seems to be most attractive. This mechanism operates in those cases when the field line curvature becomes comparable to the Larmor radius of particles. They stop being confined, and, when passing through such critical region (in the plane of magnetic equator), the pitch-angle of particles changes. The first adiabatic invariant is violated. Adiabaticity parameter $\boldsymbol{\varepsilon}$ is defined as a ratio of the Larmor radius to the radius of curvature of a field line:

$$\varepsilon = pc/(qBoRc) = \rho/Rc. \quad (3)$$

Calculation of trajectories performed in [21–24] show the regime of strong pitch-angle diffusion to occur at ε ranging from 1/10 to 1/3. In most papers it is stated that the boundary between the region of strong pitch-angle diffusion and region of complete absence of any diffusion in curvature is very sharp. On the other hand, in [25] it was demonstrated that even for quiet magnetosphere a change of regime proceeds gradually, though rather quickly. Our measurements indicate to a smooth decrease of the diffusion rate with decreasing drift shells and, consequently, with increasing radius of curvature of the field lines and with decreasing Larmor radius of particles. It is likely that the discrepancy with calculations consists in the fact that no allowance was made for the existence of fast variations of the magnetic field, capable of changing (for a time and locally) configuration of field lines.

The parasitic resonance with VLF waves on electron-cyclotron frequency was considered in paper [26]. In accordance with (1) the resonance is observed when a proton and a wave move in one direction, the field-aligned velocity of the proton should be high. As a result, this mechanism works only near the loss cone. It can explain proton precipitation of small intensity detected on low-orbit satellites, but cannot substantially reduce the lifetime of protons in the belt.

CONCLUSIONS

Losses and enhancements of intensity are balanced in the radiation belts of the Earth, and it is not easy task to check theoretical calculations experimentally. Fast increases of intensity of energetic electrons and protons at all drift shells during strong magnetic storms present such a possibility. Most predictions are confirmed by our measurements, but some distinctions and new effects are revealed. The magnetosphere trap is released from an excess flux of particles in two stages, the first one is rather fast, and the second proceeds more slowly. Such a division is observed in fluxes of both electrons and protons. The second stage is well consistent with existing concepts, while the first, fast process of losses has not been studied before.

Losses of electrons from the belt occur due to pitch-angle diffusion into the loss cone. This diffusion is caused by different mechanisms.

The first stage is developed immediately after a storm: at large increase of intensity the cyclotron instability is excited in the flux of energetic electrons. Its lifetime is 5–10 days, at $L = 2.5$ the drop of intensity is somewhat faster.

After a drop of intensity by 1–2 orders of magnitude VLF waves stop being excited, and diffusion continues with lesser strength due to parasitic resonance with VLF waves of the plasmaspheric hiss type. The lifetime varies within wide limits, from 20 to 80 days; a well-pronounced minimum is seen at the region $L = 3.5$, where a gap between the inner and outer belts is formed. The lifetime of electrons in channel 1.7 MeV is everywhere less than in channel 0.3 MeV.

At the outer shells the general behavior of the slow drop of electron flux is determined by diffusion on plasmaspheric hiss. Under increased magnetic activity the plasmasphere is temporarily displaced closer to the Earth, where increases and decreases of intensity are observed due to acceleration and release of particles into the loss cone during substorms caused by auroral choruses and whistlers. These processes are fairly well described in literature.

Finally, one more mechanism, to which are subject electrons with energy higher than 3 MeV and which revealed itself in our measurements, is connected with parasitic resonance on ion-cyclotron waves (EMIC). It operates only during magnetic storms, when these waves are generated by protons of the ring current. In the period from July 2004 to February 2005 the action of this mechanism was observed during a moderate magnetic storm on August 30, 2004 and in January of 2005 (twice). The lifetime of electrons in channel 3.4 MeV is one day or less. Model calculation predict also loss of electrons with lower energies (down to 0.5 MeV), but there is no such effect in our measurements. An increase of intensity is observed instead of drop. Apparently, th3e drop of intensity due to EMIC waves is more than compensated by a growth due to auroral choruses and whistlers.

The losses of protons on the first stage (not described previously) is most likely associated with generation of ion-cyclotron waves. Protons of the ring current can be a source of these waves only during first 1–3 days after a storm, the ring current quickly drops down at the decay phase, and the excess flux of MeV protons of solar cosmic rays, trapped and accelerated during the storm, remains to be a source. The effect of fast drop is seen in channels 1.2 and 12.5 MeV at $L = 2–3$, an accelerated drop (whose origin is not clear) being observed at $L = 2.5$.

The stage of slow drop of protons is most likely associated with pitch-angle diffusion due to curvature of the field lines. Well pronounced dependence of the loss rate on L counts in favor of this hypothesis, as well as lesser lifetime of more energetic protons. Measured lifetimes are substantially lower than calculated.

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