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STUDY OF ENERGETIC PARTICLE CHARACTERISTICS ON THE ROCKET VERTICAL-10

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Several characteristics of energetic electron and proton flux measurement on the rocket Vertical-10 are presented, particularly the altitude profiles, temporal variations of protons and pitch angle distribution of electrons. Fluctuations with characteristic periods of 11—13 sec were registered at maximum altitude in the proton flux. The use of a scanning detector of electrons $E_e > 150$ keV enabled us to detect particles within the bounce loss cone. The systematic asymmetry of the pitch angle distribution of downgoing and upgoing particles for pitch angles α and $180° - \alpha$ where α is less than the local loss cone, is found. On the basis of these measurements a relatively short lifetime of electrons $(2-5) \times 10^4$ sec is found for this region.

ИЗУЧЕНИЕ ХАРАКТЕРИСТИК ВЫСОКОЭНЕРГЕТИЧЕСКИХ ЧАСТИЦ НА РАКЕТЕ «ВЕРТИКАЛЬ-10»

В работе представлены некоторые характеристики потока высокоэнергетических электронов и протонов, измеренных на ракете «Вертикал-10», в частности, высотные профили, изменение во времени потока протонов и распределение питу-углов электронов. В потоке протонов на максимальной высоте зарегистрированы флуктуации с характеристическими периодами 11 – 13 с. Использование сканирующего детектора электронов с $E_e > 150$ кэВ позволило детектировать частицы в пределах конуса потерь. Обнаружена систематическая асимметрия распределения питу-угла α и $180° - \alpha$, где α меньше, чем локальный конус потерь. На основе проведенных измерений в данной области обнаружено относительно короткое время жижни электронов в пределах $2 - 5 . 10^4$ с.

I. INTRODUCTION

The structure of the main components of energetic particles trapped in the radiation belt — electrons and protons — can be understood in the framework of the description of their dynamics by radial diffusion inwards (to lower L shells) and losses due to the interaction of particles with the residual atmosphere and with

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waves, respectively. Today we have extensive literature concerning both measurements and theoretical descriptions of processes dealing with transport, loss and injection of energetic particles in the magnetosphere. Despite of this fact there are several unsolved questions connected with a detailed quantitative understanding of the dynamics of energetic particles in the magnetosphere. Thus for instance the mechanisms responsible for precipitating electrons in the inner radiation belt as well as in the slot region are still not understood well.

More data are needed for establishing the mechanisms responsible for precipitating electrons. In this respect the most valuable information concerns the structure of the loss cone, and direct observations of electron fluxes inside the bounce loss cone are of great importance. Experimental information on energetic loss cone electron fluxes is, however, limited mainly because the satellite instrumentation does not allow to obtain pure pitch angle distribution without masking the spatial variations of fluxes.

Measurements on vertical rockets are very important in this connection. Firstly besause they allow measurements for a relatively long time on a nearly constant L while B is changing and we can detect changes of the pitch angle distribution with altitude and secondly the good temporal resolution allows to detect the fine temporal structure of fluxes in the given directions with respect to the field line. Thus while satellite measurements of particles are usually interpreted in terms of the drift loss cone structure, rocket data make it possible to examine fluxes near the local, i.e. the bounce loss cone.

Rocket measurements of energetic particles have been performed for many years. For instance, an extensive analysis of radiation belt particles as well as of cosmic rays has already been obtained by the authors of [1] with the help of an apparatus on the vertical space sound launched in middle latitudes in the USSR up to 4000 km. Several experiments were made at higher latitudes, especially those investigating precipitation of particles and the auroral processes [2—4]. Particles of higher energies above 1 MeV were studied for instance in [5].

This work presents several results of measurements of energetic particles performed on the rocket measurements in middle latitude. The attention is paid mainly to the pitch angle distribution of electrons and temporal variations of protons.

II. EXPERIMENT

The rocket "Vertical-10" was launched in the USSR on December 21, 1981 at 21.35 local time at the latitude 48.7° vertically upward to the maximum altitude 1511 km. One of the complex of geophysical apparatuses placed there was apparatus URE-1 of Soviet-Czechoslovak production designed for measurements of electrons and protons with energies tens to hundreds keV and for measurements

of the electron pitch angle distribution. Gas-discharged detectors were used for the registration of electrons. A silicon detector with a thin window and 100 μm thickness of active layer served for proton detection.

The three-axis stabilization system of the rocket enabled to measure particles from fixed directions in space. The basic parameters of the detectors as well as acceptance angles and their orientation with respect to the vertical are given in Table 1. Detector G-1 was directed upwards to zenith, the G-2 and the Si detector were perpendicular to the vertical direction and their axes were oriented to the south. Detector G-4 was placed on the scanning platform, which enabled to change periodically the orientation of the detector axis with respect to the vertical. Scanning was performed from 0° to 180° to the vertical and half of the bounce period was 19 sec. The threshold energy for G-1 and G-2 was 30 keV, detector G-4 was covered with 100 μm of Al foil and has registered electrons with energies above 150 keV. The silicon detector registered protons with energies in the range 80—160 keV and with a sufficiently lower efficiency it registered electrons with an energy of 100 keV.

Table 1

Characteristics of detectors used in URE−1 apparatus

Detector	Type	Direction to vertical	Full angle of acceptance	Geom. factor (cm^2 . ster)	Energy interval (keV)
G 1	SBT−18	↑ → 90°	12.5°	0.017	$E_e > 30$
G 2	SBT−18	↑ ↑ 0°	12.5°	0.017	$E_e > 30$
Si	Si det.	↑ → 90°	22.5°	0.041	$E_p = 80 - 160$
G 4	SBT−18	↑ ⭿ scanning	12.5°	0.017	$E_e > 150$

The apparatus consisted of two blocks, one of them, the internal block, included electronic schemes of registration; in the other, external block all the detectors were placed. The position as well as the kind of motion of the scanning detector was marked electronically. The impulses from gas-discharged detectors were connected with intensimeters. Impulses from a silicon detector were examined by a four channel amplitude analyser. The basic interval of measurement was 160 msec. According to the counting rate in a given time interval the automatic control allowed to shorten the length of the next interval for counting to 80, 40 or 20 msec, respectively and to go back to longer intervals if the counting rate had increased.

The trajectory of the rocket, i.e. the dependence of altitude (h), L and B (in Gauss) in time is given in Fig. 1. The angle between the vertical direction and $\boldsymbol{B}$ at the top of the launch was 26.5°. The computed parameters of the geomagnetic field have shown that the rocket was in the region of stable trapping ($h_{min} > 200$ km) at altitudes higher than 1350 km and the region of the quasitrapped particle population (lost from the geomagnetic trap due to azimuthal drift in the South—Atlantic region) began at 900 km. At lower altitudes particles are lost after their first bounce in the southern hemisphere because they reach the altitude of ~200 km.

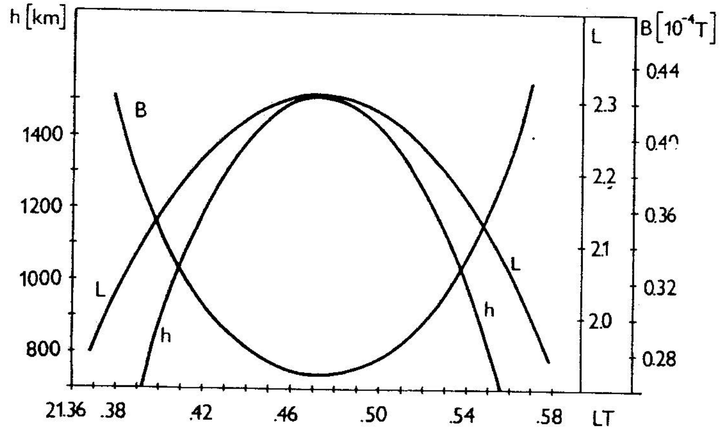

Fig. 1. The dependence of altitude (h in km), parameter L and B (in gauss) for the flight of the rocket Vertical-10.

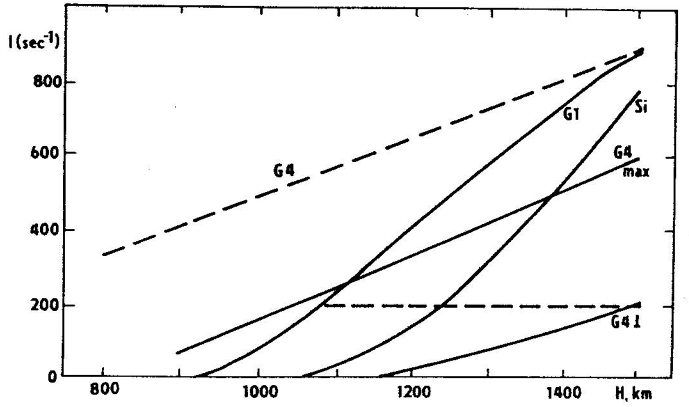

Fig. 2. The dependence of counting rates of detectors on altitude. For details see the text. The dashed line G4 is shifted up to 300 imp . s^{-1} so as not to overlap with the full line G4.

III. OBSERVATIONS

Fig. 2 gives the profiles of the couting rate of detectors in the upward part of the rocket motion. For the scanning detector G-4 data are taken at the angle of 90° with respect to the vertical (G-4) and in the position of the maximum counting rate (G-4 max) when the detector is perpendicular to the field line. The dashed curve corresponds to the expected value of the intensity at different altitudes perpendicular to **B**. These values are obtained from the pitch angle distribution at the maximum altitude and assuming the adiabatic motion of particles. At the altitude 1500 km when the rocket is for several tens of seconds practically in the same place (within 10 km), the intensity of electrons does not change and we can obtain a pure pitch angle distribution. The expected profile is in very good agreement with the measured one.

The comparison of flux values for protons and electrons shows that their ratio changes with the altitude and the steeper increase is in the proton flux. The ratio of the trapped to the precipitating electrons with an energy above 30 keV is maximal at altitudes of 1100—1200 km, then continuously decreases down to one order at the maximum altitude. The ratio of the trapped electrons $E_e > 30$ keV to those with energy $E_e \gtrsim 150$ keV is constant within the limits of error.

According to [6, 7] the intensity of protons with an energy $E_p \simeq 100$ keV at $B = 0.27$ and $L = 2.7$ is 10^4 cm^{-2}s^{-1}ster^{-1}, which means that the data on protons registered in this experiment are comparable with earlier measurements. The earlier data on electrons [8] with energies above 45 keV at invariant latitude 45—50° and at an altitude of ~1000 km give for trapped particles 2×10^5 cm^{-2}s^{-1}ster^{-1} and for precipitating particles 0.4×10^4 cm^{-2}s^{-1}ster^{-1}. The data present here are in good agreement with those numbers. For the altitude $H = 100$ km the vertical detector G-2 gives an average value 0.3×10^4 cm^{-2}s^{-1}ster^{-1} and for the horizonthal detector G-1 the value is 6.5×10^4 cm^{-2}s^{-1}ster^{-1}.

The above mentioned profiles are smoothed curves based on 1 sec averages. The real counting rate has temporal variations of course. The fluctuations of the counting rate of detector G-1, which measures electrons $E_e > 30$ keV, were not high and were limited in the range of statistically allowed fluctuations of the number of particles registered in one cycle of the telemetry write-up. The fluxes registered by silicon detector (80 keV$< E_p <$160 keV) had larger variations, significantly higher than the statistical limit. Fig. 3 shows an example of temporal variations of both detectors as measured near the top of the launch.

The pitch angle distributions of electrons obtained with the G-4 detector were analysed both on the upward as well as the downward parts of the launch. Fig. 4 shows two examples of 10° averaged pitch angle distributions obtained at different altitudes. The lower one is for the altitude just above the boundary where quasitrapping of particles is possible. The upper distribution is obtained near the maximum altitude of the flight where stable trapping is possible. Altitude changes in pitch angle distribution from ~900 km to 1511 km were examined. Qualitatively they are consistent with the adiabatic behaviour of particles in their motion along **B**. These data will be discussed in more detail in the next section.

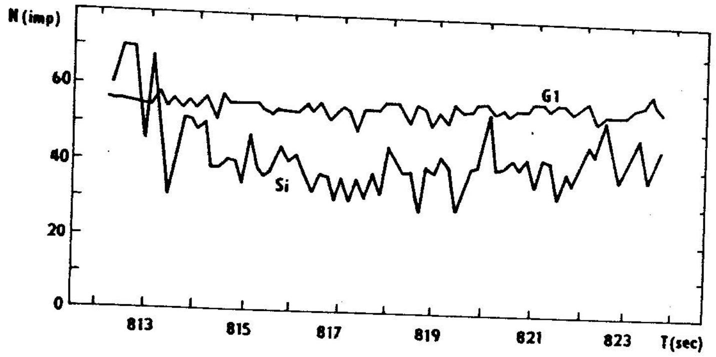

Fig. 3. Temporal variations of counting rate of silicon detector and of G1 counter. Time is in seconds after the lauch.

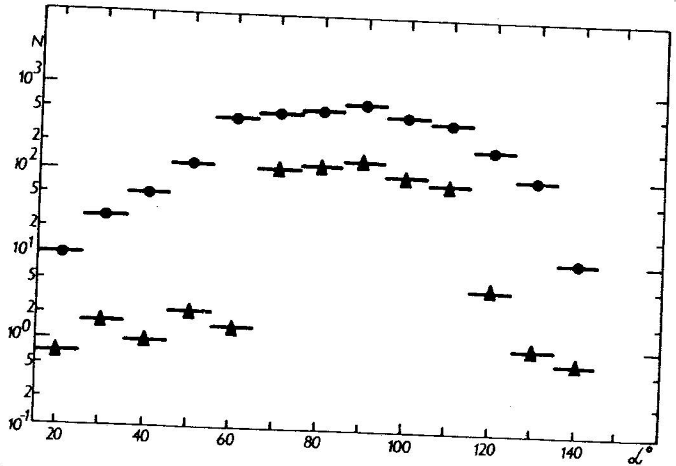

Fig. 4. Examples of pitch angle distribution of electrons $E_e > 150$ keV at two altitudes. ▲ $h = 980$ km, $L = 2.17$, $B = 0.330$, ● $h = 1490$ km, $L = 2.30$, $B = 0.270$.

IV. DISCUSSION AND CONCLUSIONS

In this part we shall interprete two measured characteristic: temporal variations obtained on the silicon detector and the shape of the pitch angle distribution of electrons.

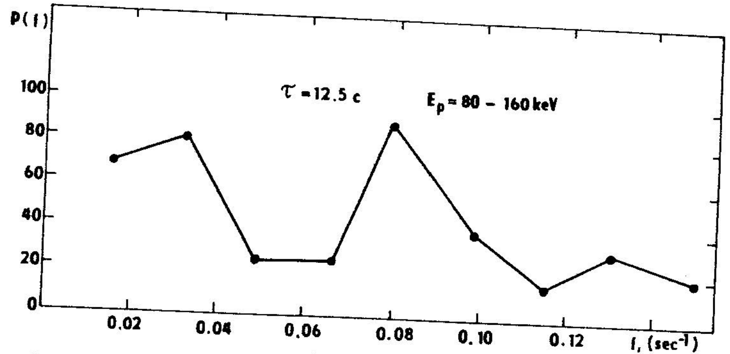

Fig. 5. Estimation of power spectrum density of temporal profile on counting rate of silicon detector for the time interval 21:48:43 UT.

The most suitable conditions for the detection of temporal variations are near the maximum of the flight. The power spectrum analysis was made for the time profile of protons in the interval 21:46:03—21:48:03, where the altitude was changed from 1491 to 1511 km. The result of the simple power spectrum analysis is presented in Fig. 5. Several intervals with a changing duration around the time of maximum flight were examined in this manner and they show a systematic increase of the power spectrum density around 11—13 sec. The periodicity in this interval can be assumed as purely temporal. Let us compare this period with the bounce period of protons. The period of bounce of particles is given according to [9]

$$\tau = 6\,.\,3 \times 10^{-2} L/\beta\,.\,f(\Theta) \qquad (1)$$

where $\beta = v/c$ and $f(\Theta)$ is a function of the equatorial pitch angle. It is changing monotonically from 1 at $\Theta = \pi/2$ to 2 at $\Theta = 0$. For out purpose the value of $f(\Theta)$ is taken as 2, since Θ is nearly 0. The obtained periodicity in Fig. 5 ($\tau \sim 12.5$ sec) is consistent with the bounce period of protons with the energy $E_p = 140$ keV. It means that the distribution of protons is not uniform in time and that they are moving in the form of packets of particles. For precipitating electrons with a much shorter bounce period the so-called microburst precipitation phenomena [10, 11] were reported — short increases with periods 0.3—0.4 sec. In [12] temporal 10 cps periodicity of auroral electron flux within the energy range 1—120 keV was reported in measurements of rocket-borne detectors. To our knowledge periodic changes of trapped protons at middle latitudes have so far not been reported. We must assume that the Si detector may measure also some portion of electrons with energies of 100—200 keV and that the effect can be masked by electron variations. Because of the low value of the bounce period for electrons (~0.4 sec)/the variations in such a case may be ascribed to the longitudinal structure of electron fluxes. The electron detectors do not record variations with the above mentioned periods, thus it seems to be more probable that we are dealing with periodicities of proton fluxes.

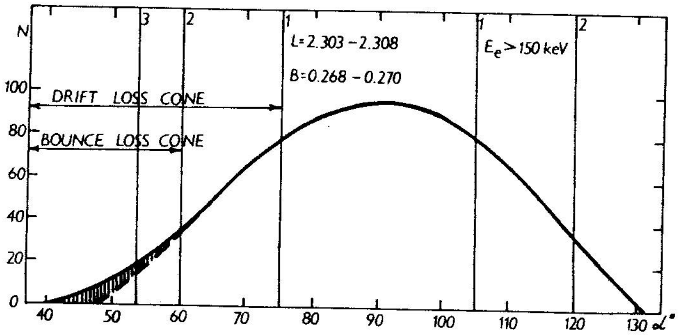

Fig. 6. Smoothed pitch angle distribution of electrons $E_e > 150$ keV around the maximum altitude $t = 21{:}46{:}43$ to $21{:}48{:}03$. Pitch angles lower than 90° correspond to downgoing particles. Vertical bars represent 1 — boundary of drift loss cone, 2 — bounce loss cone, 3 — position of detector when its full acceptance angle is within the bounce loss cone.

A more detailed analysis of the shape of the pitch angle distribution of electrons shows systematic assymmetry with respect to 90° for electrons with a relatively low local pitch angle. This asymmetry is not connected with the sensitivity of motion of the scanning device and it is apparent for half-bounces from zenith to nadir and vice versa. Four half-bounces of the counting rate of G-4 at the time of the maximum altitude of the flight were averaged and the smoothed curve of such a pitch angle distribution is given in Fig. 6. The left part of the curve (angles less than 90°) is for fluxes down to the atmosphere, the right part corresponds to fluxes upward. The asymmetry is apparent for pitch angles with a distance ± 40° from 90°. For a given point ($H = 1500$ km, $L = 2.3$, $B = 0.268$) in the geomagnetic field assuming the conservation of the first adiabatic invariant, particles with a local pitch angle 50° or less have their mirror points at $B = 0.48$ gauss which corresponds to 200 km or less and they are lost in the atmosphere. In the opposite southern hemisphere the mirror points are much lower and for the altitude of 200 km the value of $B = 0.35$ gauss. This implies that the pitch angle distribution should be much narrower and assuming the width of the acceptance angle the particles with the pitch angle 60° should not be registered. The excess of the electron flux for pitch angles lower than 60° to the flux above 120° should be ascribed to particles mirrored above the atmosphere in the northern hemisphere but are lost in the southern hemisphere.

The observed pitch angle distribution shows that in the process of electron motion from the southern to the northern hemisphere and back, i.e. in the time period equal to one bounce period, the measurable part of the electron flux is scattered so that the particles are found in the local loss cone and in the bounce period (~0.4 sec) lost in the upper atmosphere.

The essential processes in the dynamics of geomagnetically trapped radiation are radial diffusion and pitch angle diffusion. The lifetime of particles in the radiation belt is determined by the rate of these processes. For radial diffusion of electrons the characteristic quantity — radial diffusion coefficient — D_{LL} was studied extensively both theoretically and on the basis of measurements. Despite of this there is a wide range of the obtained values, particularly for L shells near our measurement (see for instance Fig. 20 in [13]). In the pitch angle diffusion the lifetime is defined usually as the ratio of the number of particles on a given energy surface to the number of particles from this surface lost in unit time. In the notation of [14] this lifetime is for the regime of weak diffusion inversely proportional to the pitch angle diffusion coefficient, while for the strong diffusion, when isotropisation of particles according to their pitch angles in the interval of the half bounce period ($\tau_b/2$) occurs, it is limited by $2\tau_b/\alpha_0^2$, where α_0 is the loss cone.

One approach to the lifetime of particles is based on measurements of the content of particles in the drift loss cone and the total content of particles in the given flux tube on the equator. It is assumed that the most rapid process leading to the replenishment of particles is their loss in the region where in the azimuthal drift their mirror points are lowering to the nominal height of the atmosphere. Practically the estimation of such a lifetime is

$$T_L = \frac{B_h}{B_{eq}} \frac{J_{eq}}{J_h} \tau_{dr} \qquad (2)$$

where B_{eq}, J_{eq} are values of the magnetic field and of the electron flux on the equator; B_h, J_h — the same values for $h_{min} < 0$. This approximation is valid if the fluxes on the equator and on the negative h_{min} are isotropic. This is not typical for low altitudes and one inaccuracy is incorporated in the assumption of the form of the pitch angle distribution. The values of the lifetime of electrons $E_e > 40$ keV were obtained by formula (2) analysing the longitude dependence of flux of electrons on a low h_{min} on different L-shells on the basis of measurements on board the Intercosmos-5 satellite [15]. The value of lifetime for $L = 2.5$ was 9×10^5 sec.

In fact this in an upper limit for the lifetime of particles neglecting the process of pitch angle scattering of particles into the local loss cone during one bounce period.

The systematic asymmetry of PAD on the Vertical-10 in the population inside the bounce loss cone provides a possibility to estimate the rate of pitch angle diffusion directly in one bounce period. The approach to the particle lifetime will be

$$T_L = \frac{B_h}{B_{eq}} \frac{J_{eq}}{J_h^*} \tau_b \tag{3}$$

where J_h^* is the intensity of electrons in the local loss cone normalized to the isotropic pitch angle distribution. According to Vertical-10 measurements formula (3) gives for electrons $E_e > 150$ keV on $L = 2.3$ a lifetime in the range $(2—5) = 10^4$ sec. For the equatorial flux we take the data of [16]. The obtained values are more than one order lower than those obtained in [15]. It should be noted that the lifetime obtained from a rough estimation of the pitch angle diffusion coefficient D on the basis of the height dependence of the electron flux $E_e > 40$ keV gave a very low value, less than 10^4 sec for $L = 2.5$ [17].

More precise theoretical assumptions of distribution of electrons near and inside the loss cone involving both the diffusion due to wave-particle interactions with atoms of the atmosphere lead to predictions of a more realistic pitch angle distributions [18, 19]. Particularly, a relatively high and energy dependent content of electrons inside the bounce loss cone and the asymmetry of downgoing and upgoing fluxes are expected. This implies that a significant fraction of the trapped flux population enters into the loss cone and it is precipitated in each quater bounce period, which results in a very short lifetime of the radiation belt electrons. In this context a valuable information on the actual diffusion coefficient is the comparison flux of precipitated electrons within the loss cone with the trapped flux outside.

The experimental investigation of particles deep within the loss cone is not easy because of a relatively low particle flux. Two facts can degrade the pitch angle distribution. The first is the contamination of other types of particles. In our experiment due to the discrimination of protons up to high energies this effect should not play any important role. The other fact is the effect of the finite acceptance angle of the detector. Although this effect could be important on URE-1, we can state that the finite flux of electrons $E_e > 150$ keV is measured by our apparatus inside the loss cone (bar 3 in Fig. 6 corresponds to the angle of the detector axis when the full acceptance cone is within the loss cone).

In order to reexamine the relatively short lifetime of electrons with an energy $E_e > 150$ keV obtained on the scanning detector we analysed fluxes of electrons $E_e > 30$ keV registered by the G-1 detector. Its axis is 63.5°, inclined to $\boldsymbol{B}$. Fluxes measured at an altitude of 950—1000 km lead to the conclusion that some fraction of electrons of these energies is found within the loss cone and is lost in one bounce period (~1 sec). The rough estimation of the lifetime is consistent with the value obtained for the electrons with $E_e > 150$ keV.

In several papers there is pointed out the role of VLF transmitters and the industrial activity in the precipitation of electrons in the inner zone [20], in the slot region [21] and on a global scale [22, 23]. In [20] electrons with energies 36 keV to 317 keV are reported to have on $1.6 < L < 1.9$ lifetimes somewhat higher than only one day and the outer edge of the inner zone is found to be controlled by wave-particle interactions, mainly due to VLF transmitters. It is possible that the short lifetimes found in the work on $L = 2.3$ should be affected by waves which are not only of magnetospheric origin. It would be interesting to compare in future experiments the shape of the pitch angle distribution of electrons with wave measurements not only at low altitudes but simultaneously on the equator for solving the question of the main cause of the pitch angle diffusion.

The short interval of the performed measurement on the Vertical-10 does not allow to conclude that the lifetime of electrons obtained here is constant and characteristic for $L = 2.3$. But the consistency of the fluxes of electrons registered here and the data obtained during several passes of the Intercosmos-5 satellite through this region under quiet conditions supports the assumption that in this region of L shells the lifetime of electrons is only several hours.

If this conclusion is correct, then there must exist in the examined region a sufficiently powerful and stable accelerating mechanism which secures the existence of such strong fluxes of the energetic trapped electrons.

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