Chapter 4

The Ion Radiation Belts: Experiments and Models

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Abstract Several years after the discovery of the Earth's radiation belts (in the mid-sixties) the model describing their formation due to geomagnetic field fluctuations and/or the electrostatic convection field was developed. This model permitted to explain many regularities of the experimentally recorded radiation belt parameters. By the present time vast experimental data on the structure, dynamics and composition of the radiation belts has been acquired. These data permit to make more detailed comparison of physical model predictions and experimental results. This report analyses the experimental data on the ion composition of the radiation belts and corresponding physical models of ion sources and transport in the trapped radiation zone.

Keywords Radiation belts, ions, protons, cosmic rays, radial diffusion.

1. INTRODUCTION

During several years after the discovery of the Earth's radiation belts (RB) (see the survey by J. Lemaire, 2001) the main attention of both experimental physicists and theoreticians was paid to the studies of the electron and proton trapped radiation components. Primarily this was caused by inadequate development of experimental techniques, which did not permit to measure ions, heavier than protons. As a result our understanding of the RB at that time was that their predominant component consisted of protons.

However, somewhat later experimental evidence was obtained, that heavy ions play a significant role in the development of several dynamic processes in the magnetosphere. Experimental studies of ions (with different mass, charge states and energy) are an efficient tool for revealing the regularities in the formation of the spatial-energetic trapped radiation

I.A. Daglis (ed.), Effects of Space Weather on Technology Infrastructure, 65-90.

structure in the vicinity of the Earth. These studies also permitted to establish the possible sources of trapped radiation in the Earth's vicinity.

It is generally accepted that the lower energy boundary for RB particles are tens of keV, i.e. particles with energies close to those of the ring current. The minimum energy of RB ions can be determined as the energy of a population of particles which are subject predominantly to magnetic drift in the geomagnetic field, unlike ring current particles, since their dynamics is determined by drift in the geomagnetic and electric convection fields. The upper energy of RB ions is determined by the condition of stable trapping in the geomagnetic field according to the Alfven criteria:

$$\rho_L / \rho_m << 1 \qquad (1)$$

Where ρ_L is the particle Larmor radius and ρ_m is the curvature radius of magnetic field line. The maximum particle energy for ions depends on L-shells, and charge state. For protons these energies are of the order of hundreds MeV in the inner radiation zone, i.e. the maximum energy of RB protons coincides with the minimum energies of galactic cosmic rays (GCR). It were GCR that became the first candidate for the source of RB particles, however, later it was discovered that they were by far not the only one. We will consider the possible sources of RB ions and the experimental data confirming their existence.

The structure of the ion RB unlike that of the electron RB, is described by single-maximum profiles of particle intensity with E=const. According to the theory of Tverskoy (1965), the location of ion maximum intensity L_{jm} is determined by the balance equation (see Fig.1):

$$\tau_t(L) \approx \tau_s(L) \qquad (2)$$

where $\tau_t(L)$ is the particle lifetime on a given L- shell controlled by losses, and $\tau_t(L)$ is the particle transport time from the RB boundary to a given $L = L_0$.

Studies of RB ions besides their fundamental aspect also have important applications in such aspects of space physics as 'space weather'. In particular, these applications include phenomena associated with radiation effects (dose effects and single event upsets) and human safety in space (see e.g. the surveys by Panasyuk, 2001and Baker, 2001).

This paper gives an overview of the main experimental results and corresponding physical models, which permit to explain the possible sources, acceleration and transport mechanisms of RB ions.

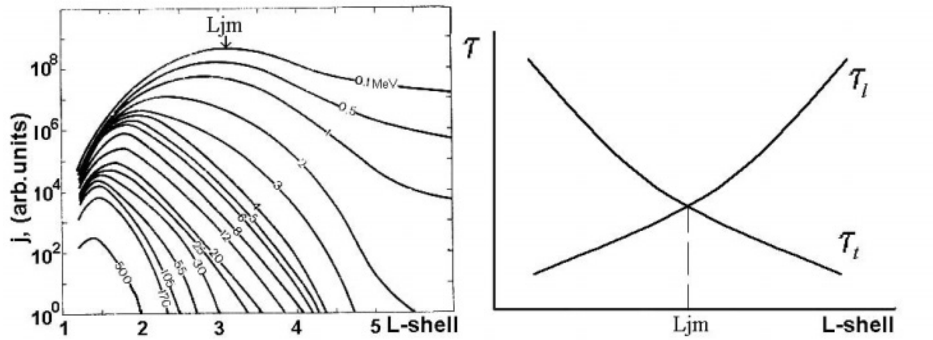

Figure 1. Radial profiles of the equatorial intensities of RB protons with different energies (left panel) and schematic drawing of the transport $\tau_t(L)$ and loss times $\tau_l(L)$ (right panel). The balance $\tau_t \approx \tau_l$ determines the location of maximum intensity for the radial profile L_{jm} of protons (and other ions).

2. SOURCES

2.1 Galactic Cosmic Rays

At present the acquired experimental data is sufficient to prove that this space radiation component as an important source of RB particles. The CRAND (Cosmic Ray Albedo Neutron Decay) mechanism – neutron decay leading to _ generation of secondary protons and electrons ($n \rightarrow p + e + \nu + 782keV$) became the first physical mechanism describing the origin of RB particles.

GCR particles, which have significant momentum, penetrate inside the Earth's magnetic field, reaching the atmosphere they interact with atmospheric nuclei producing neutrons. The products of neutron decay (protons and electrons) become trapped in the geomagnetic field and undergo diffusion transfer, getting accelerated due to betatron acceleration. This scenario was simulated in numerous works and the results give good agreement with experimental data. Apparently there are no reasons to doubt that GCR particles are responsible for the population of the inner RB region (on L<2) with energies exceeding tens of MeV. (see e.g. the model Beutier, et al., 1995).

2.2 Anomalous Cosmic Rays

GCR have a low-energy anomalous component (ACR) (^{16}O, ^{14}N, ^{20}Ne and other ions with energies of 10-20 MeV/nucl which can penetrate inside the geomagnetic field like the main GCR component, since, as a rule, they have the minimum charge state of Q=1+. However, the mechanism of 'secondary' particle production in this case is different. Reaching the atmosphere ACR undergo charge-exchange on neutrals. The charge-exchange products (stripped heavy ions) are trapped by the geomagnetic field, forming a radiation belt. This mechanism was suggested by Blake and Friesen (Blake, Friesen (1977)) and was confirmed in a number of experiments. The first experimental indications of the possibility of the formation of a RB containing ACR ions appeared in the works of Biswas (see e.g. Biswas et al. (1980)). The final proof of the existence of such belts was given in the works of the Russian-American collaboration (Grigorov et al., 1991) and later in the experiment on SAMPEX (Selesnick et al., 1997).

Trapped ACR form a radiation belt on $2<L<3$ and their flux exceeds the flux of ACR in the interplanetary medium by a factor of hundreds. Their lifetimes are quite short (~ months), which is confirmed by practically full coincidence of solar-cycle variations of trapped and interplanetary ACR ions (see Grigorov, et al., 1991).

2.3 Albedo Particles

Besides albedo neutrons from GCR and ACR, undergoing charge-exchange in the atmosphere, there is also experimental evidence confirming the existence of proton and other ion fluxes under the RB, in regions below the geomagnetic cut-off threshold. The origin of these fluxes in not fully understood. These particles can be considered as a potential source of trapped particles in the RB, however, the efficiency of this process also needs additional investigation.

The first indication of the existence of the so-called 'excess radiation' appeared as far back as the middle of the 60-ies . According to data of the 'Cosmos-721' satellite (Basilova, et al. (1973)) the total flux of albedo protons with rigidities R >8-10 GV at altitudes of 200 km near the equator exceeds the flux of primary GCR. According to data of the 'Coronas-I' satellite (Kuznetsov, et al. (2002)) on L=1.1 and 1.6 significant fluxes of albedo protons with $E>$ 80 MeV were observed. These fluxes displayed significant azimuthal asymmetry.

Recently the AMS-01 experiment recorded a very accurate proton spectrum in the region below the geomagnetic cut-off threshold. It is noted, that the fluxes of secondary particles are concentrated in the vicinity of the equator with significant azimuthal asymmetry. Calculations show, (Plyaskin, 2001) that the presence of these particles is due to the complicated GCR drift trajectories in the geomagnetic field. The long-living component of this population of particles occupies an intermediate position between stably trapped and quasi-trapped particles. They can be considered as the source of particles for the inner RB zone. However, the problems associated with stable trapping of particles with such large rigidities should be thoroughly investigated.

2.4 Solar Energetic Particles

Solar energetic particles (SEP) generated on the Sun during flares or in the process of coronal mass ejections (CME) are surely among the main candidates for the RB particle source. SEP can penetrate inside the magnetosphere to relatively deep L-shells; and during powerful geomagnetic disturbances SEP fluxes are observed in low-altitude (~ 400 km) orbits (LEO).

However, the issue arises of how efficient the mechanism of SEP trapping is for increasing the population of the RB. Some doubts arise as a result of estimating the expression ρ_L / ρ_m (see (1)) for these particles. It should be expected, that the lifetimes of SEP particles inside the RB should be relatively small due to their large rigidities. For SEP protons this effect is vividly demonstrated in many experiments: the gyro-radius of energetic protons is comparable with the curvature radius of the field line in their penetration region (as a rule it is the outer region of RB), therefore, protons leave the trapping region. This effect is enhanced during magnetic storms, when a depression of the magnetic field in the outer RB regions is observed. Hence, the probability of observing long-living SEP protons inside the RB after disturbances on the Sun is small.

We would also like to draw attention to another effect, giving evidence in favor of this statement.

It is known, that for SEP the ratio He / H ~4÷5%. Therefore, it seems reasonable, that for those RB particles which are not subject to losses (e.g. $\tau_t(L) > \tau_s(L)$) similar abundances of these elements should be observed, if their source is SEP.

A characteristic feature of the RB ion energy spectra is their form which displays a maximum. The location of the maximum E_m is determined by losses (Coulomb losses and charge-exchange). At $E > E_m$ the relative abundances of ions should be determined by their source, i.e. the spectrum at the RB boundary. The 'footprints' of SEP inside the RB should be sought in the energy range of several MeV and more. Fig. 2 demonstrates the energy spectra of near-equatorial protons and He ions on L=2.5; 2 and 1.7 (the lower part of Fig.2).

The upper panel of the figure shows the He/H ratio for E/A=const. As it can be seen from the He/H energy dependence, in the energy range $E > E_m$ the value of He/H hardly reaches 10^{-1}. Therefore, if the influence of SEP on the stationary structure of the ion RB can be manifested, it is only on the high energy tails of the energy distributions in the inner RB zone.

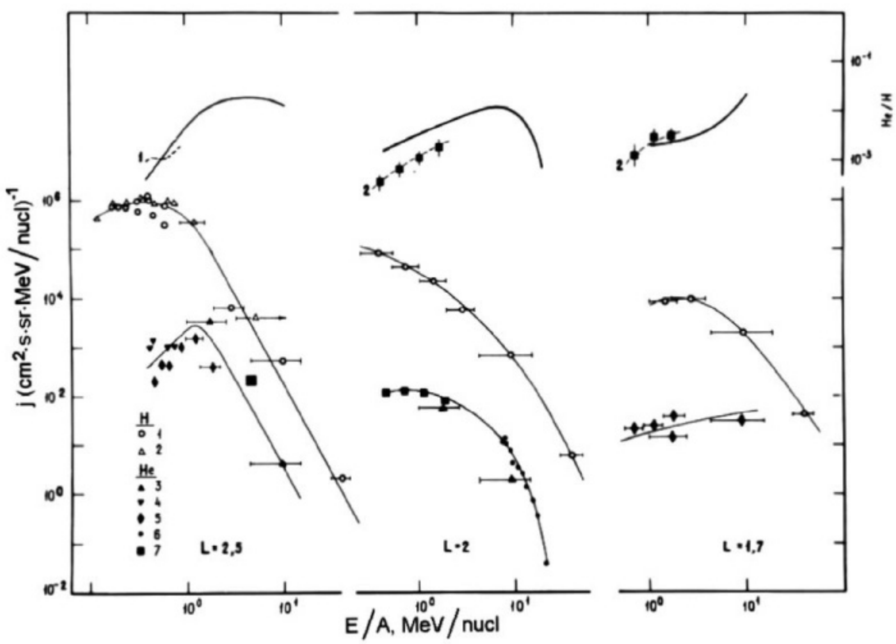

Figure 2. The differential energy spectra of near equatorial H and He fluxes in the inner zone of the RB (the lower part of the figure). References to experiments (1-7) can be found in (Panasyuk, 1983). The upper part of the figure shows the dependence He/H(L) obtained from experimental data approximations.

2.5 Nuclear Reaction Products

The radial intensity profiles of the ion RB have a typical maximum (see Fig.1). The location of the maximum on a certain L-shell is determined by the balance between the transport velocity and particle losses during radial diffusion. However, in a number of experiments measuring ions of He and heavier elements a second intensity maximum, located on L-shells deeper than the diffusion maximum, was discovered. One of the first observations of this maximum (see Fig.3) was the made in the experiment on ‘Intercosmos-17’ (Kuznetsov, 1988).

The authors suggested a mechanism for the trapping of nuclear reaction products, generated as a result of high energy (~100 MeV) RB proton interactions with the residual atmosphere (thermal oxygen and helium). Proof of the existence of heavy nuclei fluxes (He, CNO) in the inner RB zone was obtained in other experiments, e.g. on SAMPEX (Cummings, et al. 1994). Therefore, the existence of heavy ions as the products of nuclear reactions in the residual atmosphere can be considered proven.

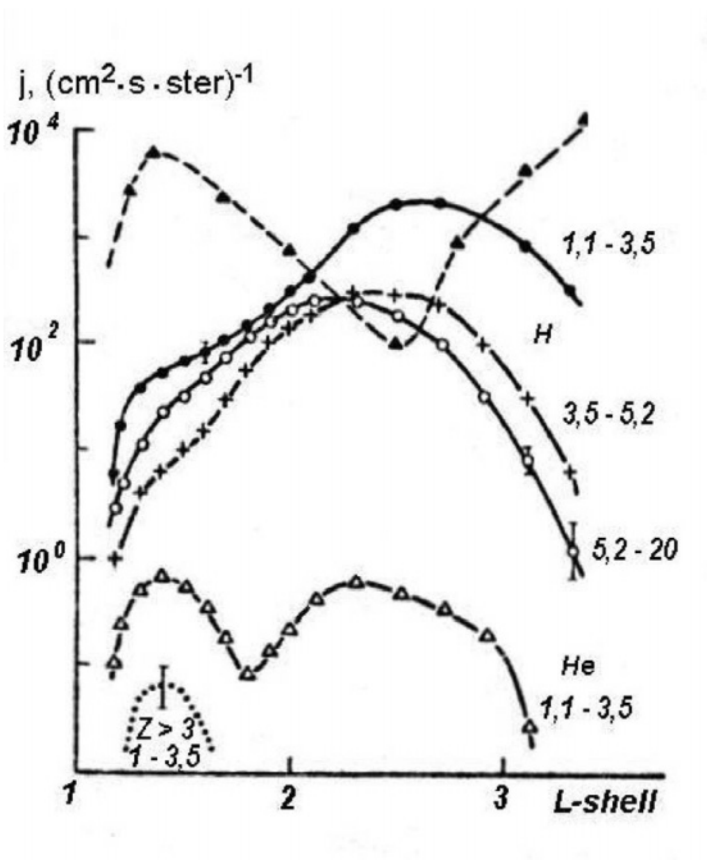

Figure 3. The radial intensity profiles for H, He, and ions with Z>3 of different energies (MeV/nucl) according to data of Intercosmos-17 (Kuznetsov, 1988) at altitudes of ~500 km.

2.6 Plasma Sources

The plasma sources of the ion RB include plasma of solar origin (solar wind) and ionospheric plasma. The major difference between these sources is the elemental composition and ionisation state of the particles.

Solar plasma is characterised by a high content of ^{12}C (C/O~1) and high charge states of heavy ions. The ionosphere has low relative content of ^{12}C (C/O~10^{-5}) and low charge state of such ions as He, N and O (see the survey by Kremser, et al., 1989). It is these parameters of the ion composition that can serve as indicators of the efficiency of these sources. Evidence in favour of high efficiency of the solar source comes from measurements of the relative content of energetic (in the MeV range) C and O ions in the RB. Fig. 4 demonstrates the energy spectra of H, He, C and O in the near-equatorial plane on L=4 and L=5. The data of ISEE-1 (Hovestadt , et al., 1978) on C and O confirm a high (close to ~1) relative content of C and O, which corresponds to the solar source (both for solar wind and SEP).

Other proof of the efficiency of the solar source could be obtained from determining the charge state of heavy ions in the RB. There are no direct experimental techniques for determining the charge states of ions in the MeV energy range. Therefore, we can once again use the criterion for stable trapping of particles (1) in order to estimate their charge states. From (1) we can obtain:

$$E_c\,(\text{MeV}) \approx 2{\cdot}10^3\, Q^2 / A L_c^4 \qquad (3)$$

In expression (3) Q is the charge state of ions, A is the ion mass number, L_c is the outer edge of the intensity profile for particles with E=const. An estimate of L_c according to experimental data (for references see Panasyuk, 1982) gives the possibility to determine Q for different ions. For the first time L_c was used as the stable trapping boundary for protons with a fixed energy in the work of Ilyin, et al., (1986) to determine the constant $\varepsilon = \rho_L / \rho_m$, which was found to be ≈ 0.1.

The results of estimating Q using experimental data on L_c for near equatorial He, C and O ions are shown in Fig. 5 These results give convincing evidence that $Q(He)$=2+ and $Q(C,O)$>5-6+ are close to their maximum values. These estimates of Q for He, C and O in the MeV energy range agree with the results of determining energetic ion charge states according to such events as the ‘drift echo’ in geostationary orbits (see e.g. Sibeck, et al., 1988).

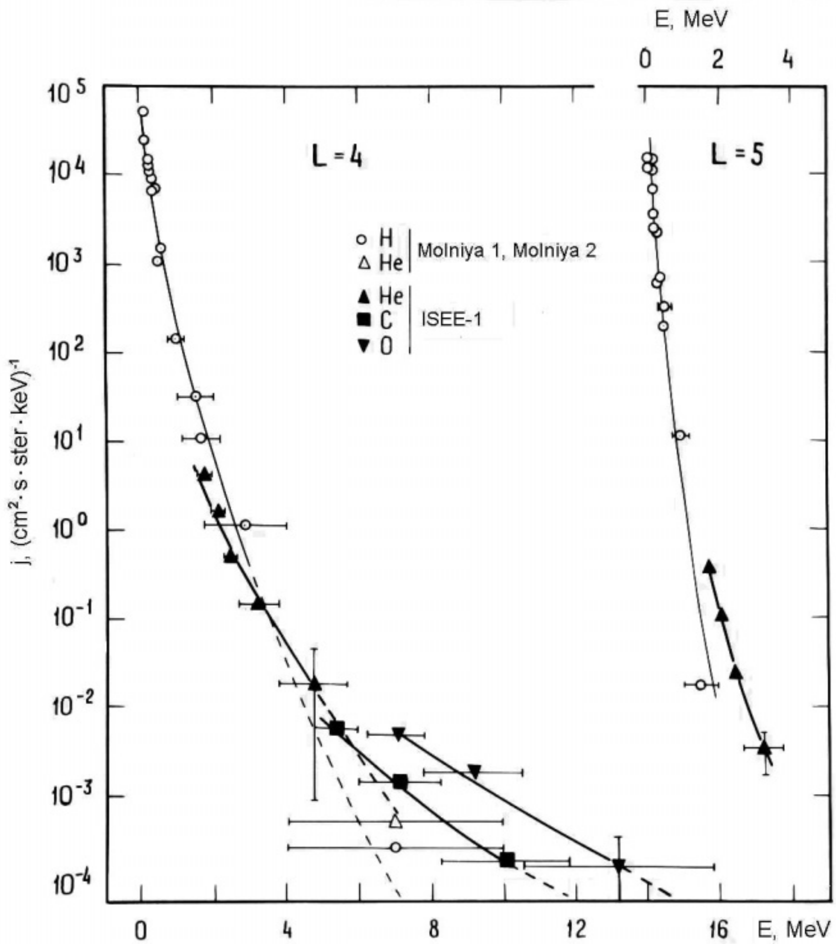

Figure 4. Averaged equatorial spectra of H and He ions on L=4 and L=5 according to data of the Molniya-1 and ISEE satellites. The solid lines are an approximation of the exponential function $j_i(E) \propto \sqrt{E/E_i^*}\exp(-\sqrt{E/E_i^*})$, which demonstrates, scaling of the energy spectra $E_i^* = QE_H^*$, where Q is the charge state of ions in the solar source, E_H^* is the characteristic energy for H.

Estimates of charge states obtained using the dispersion pattern of particle drift also gave Q=2+ for He with energies of hundreds of keV and Q=5+ for $[C,N,O]$ with E>1 MeV. The presence of hot *ionospheric plasma* (i.e. particles with energies E>10 keV) inside the trapped radiation zone has been confirmed in many experiments (see e.g. the survey by Daglis, 2001).

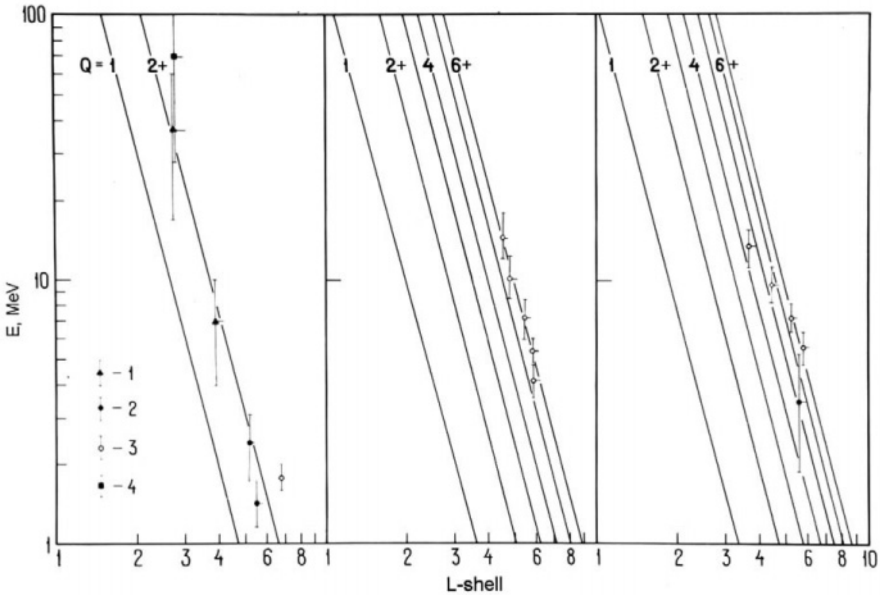

Figure 5. Determining the charge state of ions using expression (3). The lines are calculation results for different values of Q. The values corresponding to the locations of the outer edges of the ion RB - L_c were taken from experiments 1-4 (see text)

The ring current injected inside the RB during magnetic storms mostly consists of H and O ions. The charge distribution shows that the ring current contains both multiply and singly charged ions (Kremser, et al. 1989). This could serve as evidence that the ring current contains ions of both solar and ionospheric origin. However, charge-exchange processes, leading to both increase and decrease of the ion charge states, transform the spectrum typical for a certain source. Therefore, estimates of the relative contribution of these two different sources according just to their charge states can hardly be accurate. Estimates of the contributions of solar and ionospheric sources were also made using comparison of the relative content of He^{2+}/H. However in this case the final conclusions can also hardly be made, since it is impossible to distinguish between ionospheric and solar H, and for He^{2+} the comments made above are also true.

Nevertheless, on the outer shells of the trapping region (e.g. in geostationary orbits), i.e. where transport processes dominate over losses, such estimates can be valid.

At present many authors assert (see the survey of Daglis, 2001), that the relative contribution of the two sources varies depending on the magnitude of magnetic storms. With increasing values of the Dst index the contribution of the ionospheric source (which mostly consist of O^{+} ions) increases. In other words, in large and gigantic geomagnetic storms ions of terrestrial origin dominate. The mixture of plasma particles of solar and ionospheric origin in the ring current is definitely one of the main sources of RB particles. Here once again the issue which of the ring current populations has predominant influence on the stationary structure of the ion RB arises.

For the first time this issue was studied by Spjeldvik and Fritz, who developed models of the heavy ion RB (see e.g. Spjeldvik, Fritz, 1978). The author simulated RB, consisting of heavy ions. The spectrum in the diffusion equation was taken as containing either particles of solar (He^{2+}, O^{8+}) or ionospheric (He^{+}, O^{+}) ions. The obtained result confirms that the initial charge states of ions are transformed during their transport inside the RB. Hence, it was shown, that the main charge states of O ions with energies exceeding hundreds of keV in the core of the RB is ~ 4+. This makes it impossible to identify experimentally the distribution of particles associated with charge-exchange in those energy ranges where losses dominate.

Similar modeling of He and O in the RB taking into account the solar source, or the ionospheric source, or both these sources of particles was made in Belyaev et al. (1995), but with diffusion coefficients different from those used in the model of Spjeldvik. Diffusion coefficient D_m and D_e corresponding to experimental data on the structure of the ion RB were used. The obtained result is close to the conclusions made by Spjeldvik: the nature of the source does not significantly influence either the charge or energy distributions of ions in the space-energy region where losses dominate (particles with energies exceeding several hundreds of keV on $L \leq 3$).

2.7 The Form of the Injection Spectrum

The currently available experimental data confirm the existence of stationary fluxes of energetic He, C and O ions in the RB predominant over H fluxes at constant energies (see Panasyuk et al., 1977; Spjeldvik, Fritz, 1978; Panasyuk, 1982). In geostationary orbit (L=6.6) an excess of He over H is observed at $E \geq 1$ MeV. In this region the fluxes of O and C exceed the fluxes of He, and $O/H > C/H > He/H$ (Konradi, et al. 1980). Inside the RB a similar pattern is observed for more energetic particles (see Fig. 4).

The author of this work suggested an interpretation of the energetic ion space-energy structure, basing on the existence of E/Q scaling for the exponential energy distributions of ions in the RB (Panasyuk, 1982). In scope of this idea the existence of dominating ion fluxes at E=const can be easily explained. Simulations have shown, that the use of such solar wind parameters as the charge states Q=2+ for He and $Q = 5 \div 6$ for C and O, along with relative concentrations of these ions give satisfactory agreement with the spectral characteristics of these ions inside the RB. In other words, the energy distribution of RB ions are invariant in the E/Q representation, where Q is the ion charge state, typical for the solar wind. In Fig. 4 an example of such simulation and comparison for L=4 and 5 are shown.

The temperature of the solar corona mainly determines the charge state of the solar wind. Therefore, the observed E/Q scaling of the energy distributions is evidence, that they are a 'response function' of the solar corona temperature.

Can this conclusion be extended to smaller energies, e.g. the ring current or the plasma sheath? We can mention a number of results confirming the existence of E/Q scaling of the ion energy distributions, for both the plasma sheet and the ring current ions. (See e.g. Kremser, 1989). There are cases of E/Q invariant distributions of thermalised particles in the cusp (see Fritz et al., 2002). However, such structure of the distributions is not always observed and significantly depends on geomagnetic activity. (See Kovtyukh, 1999). So far, we can state, that E/Q scaling exists for the energetic component of RB particles, and extension of this conclusion to smaller energies is subject to discussion.

E/Q scaling of the energy distributions is of principle importance for RB particles, since solar plasma and SEP particles typically have energy distributions (distribution functions) in velocity. This can be an indication of the existence of a magnetospheric acceleration mechanism, transforming the initial distributions of solar particles, and forming the RB particle injection spectra with E/Q scaling.

3. ION TRANSPORT

3.1 Diffusion equation for ion transport in the radiation belts

The Fokker-Plank equation describes stationary space-energy distributions of particles inside the radiation belts. For particles with pitch-angles α=90° it has the form:

$$L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f_i}{\partial L}\right) - \frac{G}{\sqrt{\mu}}\frac{\partial f_i}{\partial \mu} - f_i \Lambda_{ce} = 0 \quad (4)$$

In expression (1):

f_i is the distribution function for *i*- type ions; μ is the magnetic moment; G is the Coulomb factor, Λ is the term describing the charge-exchange process and D_{LL} is the radial diffusion coefficient.

The efficiency of particle transport inside the magnetosphere is determined by D_{LL}. The magnetic and electric diffusion coefficients D_m and D_e are determined by the power spectra of the azimuthally symmetrical parts of fluctuations for the electric $P_e(\nu)$ and magnetic $P_m(\nu)$ fields at ion azimuthal drift frequencies $\nu = \nu_d$.

Taking into account the first spatial harmonic of the Fourier spectrum for the asymmetric part of the field fluctuations of α=90° particles we can write D_{LL} (Falthhammar,1966) as:

$$D_m \propto \nu_d^2 P_m(\nu_d) L^{10} \qquad (5)$$

$$D_e \propto P_e(\nu_d) L^6$$

If $P_{m(e)}$ depends on the drift frequency as $P_{m(e)} \propto \nu_d^{-p(l)}$, where p and l are indices of the fluctuation power spectrum for magnetic and electric fields respectively. From (5) it follows, that for arbitrary values of $p(l)$ the diffusion coefficient $D_{m(e)}$ will differently depend on L, particle energy E and charge state Q, since $\nu_d \propto \mu / L^2 Q$, where μ is the ion magnetic moment.

From (5) the expression for $D_{m(e)}$ in general form can be written as:

$$D_{m(e)} = C_{om(e)} \left(\frac{\mu}{Q}\right)^{v_{m(e)}} L^{u_{m(e)}} \qquad (6)$$

where $v_{m(e)}$=2-p and u_m=2$p+l$ for magnetic diffusion and $v_e = -l$, u_e=6+2l for electric and $C_{oe(m)}$ are constants of the diffusion coefficients $D_{m(e)}$. The form of $D_{m(e)}$ according to (3) is valid for power-law fluctuation power spectra of the electric and magnetic fields.

Unlike the power spectra of the geomagnetic field, characteristics of electric convention fields have not been well studied experimentally. Our knowledge of these fields was mainly obtained in observations of cold and hot plasma, whistlers and other magnetospheric phenomena (see e.g. Carpenter ,1972 ; Caufman, Gurnett ,1972; Volland ,1973; Galperin et al., 1980; Mozer,1971; Holthworth, Mozer,1979; Andrews,1980).

From the point of view of revealing the relative importance of each of the transport mechanisms it is necessary to take into account the following circumstances. According to a number of models, during the movement of hot plasma in the plasma sheath (ring current injection) for a uniform magnetic field a gradient drift (current) arises in the azimuthal direction. This drift causes depletion of the electric convection field in the inner regions of the RB and induces longitudinal currents near the inner boundary of the plasma sheath (see e.g. Alfven, Falthammar ,1967; Tverskoy,1970. There are numerous experimental results (see e.g. Gurnett, Frank,1973; Mozer, Lucht,1974; Southwood, Kaye,1979), which give evidence in favor of electric fields attenuation on L<4. Therefore, it can be expected that the efficiency of electric diffusion decreases in the inner RB regions. Therefore, postulating the uniformity of electric fields in the whole RB region as, for example, it was done in the ion RB models of Cornwall (1968); Cornwall(1971), and later in Spjeldvik (1977) and others is an idealization of the actual convection electric field distribution pattern inside the RB.

However, we should take into account, that for arbitrary field fluctuation power spectra, the structure of the ion RB should be determined by both the amplitude and indices of these spectra. Since $D_{m(e)}$ have different dependencies on L, E and Q, comparison of experimental data on the structure of energetic RB ions is important for determining the predominant mechanism responsible for radial transport.

3.2 Experimental verification of magnetic and electric diffusion efficiency

The particle transport time from the RB boundary (L_b) to a given $L = L_o$ can be written as:

$$\tau_t = \int_{L_b}^{L_0} (\partial L / \partial t)^{-1} \partial L \tag{7}$$

where $\partial L / \partial t = -2\partial D / \partial L + 2D / L$ is the particle radial transport velocity. Using expression (1,6) and (7) , and taking into account only the Coulomb losses, we obtain the dependence for $L_{jm}(E)^*$:

$$L_{jm}^{m(e)} = a_{m(e)} E^{S_{m(e)}} \tag{8}$$

where the $m(e)$ indices correspond to magnetic and electric diffusion respectively.

It should be mentioned, that the slopes $s_{m(e)}$ of the energy dependence $L_{jm}(E)$ are determined as:

$$s_m = (p-3.5)/n - p + 10$$

(9)

$$s_e = (l-1.5)/n - l + 4)$$

i.e. depend both on the spatial distribution of the concentration of cold electrons $N_e \propto L^{-n}$ and on the form of the non-stationary field power spectrum ($(P_{m(e)} \propto \nu^{-p(l)})$.

Besides, L_{jm} for different types of ions at s=const, E=const should differ and their ratio (r) can be described as:

$$r_{m(e)} = L_{jm}({}^{A}I^{Q+}) / L_{jm}({}^{1}H^{+}) = \begin{cases} (A^{0.5}Q^{4-p})^{\frac{1}{n-p+10}} \\ (A^{0.5}Q^{2-e})^{\frac{1}{n-l+4}} \end{cases} \quad (10)$$

The conclusions which follow from expressions (7,8) are the following:

1. $s_{m(e)}$ and $r_{m(e)}$ decrease with increasing slope of the cold ion concentration profile $N_e(L) \propto L^{-n}$ and with softening of the $P_{m(e)}$ power spectra.

2. Taking into account that for $N_e(L)$ in the plasmasphere $n \geq 0$, and that definitely it can be expected that $10 \geq p \geq 0$ and $4 \geq l \geq 0$, we come to a more rigid constraint on the slope indices p and l:

a) if $s > 0$, then $p > 3.5$ and $l > 1.5$;

b) if $s < 0$, then $p < 3.5$ and $l < 1.5$.

It should be mentioned, that in a number of models it was assumed (see e.g. Cornwall,1971; Spjeldvik, 1977) that $p = l = 2$. This leads to the opposite slopes for the $L_{jm}(E)$ dependence: $s_m < 0$ and $s_e > 0$. A positive slope $s > 0$ contradicts experimental data. For joint action of both magnetic and electric diffusion this paradox can be resolved only by decreasing the efficiency of electric diffusion (in comparison with magnetic) for RB particles, i.e. a decrease of the electric diffusion coefficient relatively to the magnetic one.

In order to determine the efficiency of one or another transport mechanism it is very convenient to use the experimental energy distributions $L_{jm}(E)$. It is here, that the structure of the ion RB specifically helps to solve the multi-parametric problem of determining the input parameters for the particle transport equation. We will consider these results in more detail.

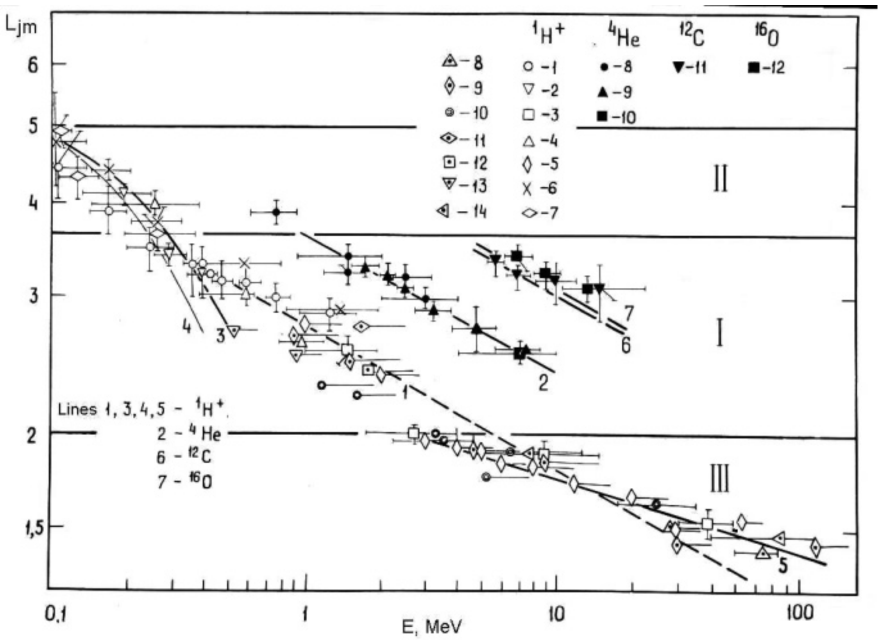

Figure 6. The energy dependence for the maximums of equatorial flux radial profiles L_{jm} for H, He, C and O according to data of experiments 1-12 (see text)

Figure 6 shows the data on L_{jm} for H, He, C and O ions during magnetically quiet times near the geomagnetic equator obtained in different experiments (for references see Panasyuk,1984). The main conclusions, which can be drawn from the analysis of these results are the following:

1. The L_{jm} dependence for protons cannot be represented by a single power law dependence $L_{jm} \propto E^s$ with s=const. Three energy ranges for protons where the s parameter is different (I, II, III) can be pointed out. The experimental data for He, C and O are insufficient for making a similar conclusion.

2. In the core of the RB on $3.5 \leq L \leq 2$ curves 1 and 2 correspond to the approximation L_{jm}=2.8$\cdot E^{-0.18\pm0.03}$ for protons and L_{jm}=3.5$\cdot E^{-0.18\pm0.03}$ for He ions. In concordance with this it follows from (8) that r=1.3±0.02 Using these estimates we defined the values of $\overline{p}$, $\overline{l}$ and $\overline{u}$ from expressions (7,8) (considering magnetic and electric diffusion to be independent). These results are brought together in Table 1.

Ions	$\overline{p}$	$\overline{l}$	$\overline{n}$	$C_{om}(e)$
H^+	2.2±0.5		0±1.4	$(1.8^{+8.1}_{-1.6})\cdot 10^{-14}$
H_e^{2+}	2.1±0.4		0±1.2	$(1.2^{+6.0}_{-0.5})\cdot 10^{-14}$
H^+		0.3±0.5	3.6±1.2	$(8.1^{+14.4}_{-5.0})\cdot 10^{-12}$
H_e^{2+}		0.1±0.4	3.8±1.2	$(3.3^{+4.4}_{-1.8})\cdot 10^{-12}$

Table 1. The calculation results for $\overline{p}$ $\overline{l}$ $\overline{n}$ and various space-weather environments and $C_{om}(e)$.

Using the obtained values of $\overline{p}$, $\overline{l}$, and $\overline{n}$ and assuming N_e=10^3 cm^{-3} on $L=3$ (which agrees with numerous experimental data, see e.g. Kawashima et al. (1984)) estimates of C_{0m} and C_{0e} were made. The value of C_{0m}=(1-10)·10^{-14} is in good agreement with average disturbed conditions in the magnetosphere at K_p=2÷3. (Panasyuk, Sosnovets ,1984). It is also in good agreement with the conclusions of the magnetic diffusion model developed by Tverskoy (1964, 1965), where C_{0m} was calculated using the statistical distribution of SSC geomagnetic disturbances. The values p=2 and n=0 also concur with this model. It should be noted, that the value of p=2 for the magnetic fluctuation spectrum assumes that D_m does not depend on E, Q and A of the ion components.

Basing on the conclusion that magnetic diffusion is predominant in region *I* of the RB and using expressions (7,8) we can obtain $L_{jm}(E)$ for C and O ions under the assumption that their mean charge states are $\underline{Q}$=5+ and 6+. Calculations give satisfactory agreement with the experiment (curves 6 and 7 for C and O in Fig. 6)

On the other hand, the attempt to explain the distribution $L_{jm}(E)$ for H and He using only electric diffusion encounters difficulties, since a flat spectrum of electric field fluctuations hardly corresponds to theoretical and experimental results (see, e.g., Andrews ,1980 where $l \approx 1$).

3. Assuming, that the values of the $C_{0m}(e)$ diffusion coefficients defined for region *I*, are preserved for the outer RB region *II* (L<3.5), the dependencies of $L_{jm}(E)$ were calculated for protons with account for their charge-exchange on neutrals of the exosphere with the temperature of T_{ex}=950K (Panasyuk,1984). Comparison of the curves describing magnetic diffusion – 3 and electric diffusion – 4 shows, that in the case of electric diffusion C_{0e} needs to be increased by a factor of ~5 in comparison to that of region *I* in order to achieve satisfactory agreement with experimental data.

On the other hand, magnetic diffusion with $C_{0m} \approx 2 \cdot 10^{-14}$ s^{-1} gives us satisfactory agreement both in region RB(*I*) and RB(*II*).

Summing up the analysis of the $L_{jm}(E)$ dependence for ions on $L > 2$, we can make the following conclusions:

Agreement between calculated and experimental data on L_{jm} for H, He, C and O ions on 2<L<3.5 is achieved either for a flat electric field fluctuation spectrum with $l \approx 0$, or for a magnetic field fluctuation spectrum with $p \approx 2$. The shape of the electric field spectrum with $l \approx 0$ does not agree with the results of direct measurements on L=6 (Holthworth, Mozer, 1979) and on L=2,3 (Andrews ,1980). On the other hand, a softer spectrum of electric field fluctuations with l>0 cannot explain the flux distribution at these L-shells for energies of hundreds of keV and more. In the outer region, as it was mentioned above, the presence of solely magnetic diffusion is sufficient to explain the proton RB structure. This leads to the conclusion that the role of electric diffusion on L>2 is insignificant.

Let us now consider the inner zone of the RB - *III*.

4. In the inner region *III* a different slope is observed $s \approx$-0.1 (line 5). If we assume that the power spectra for both magnetic and electric fields preserve their shape in the inner region of the RB this leads to a cold plasma distribution which is too steep ($\bar{n}$>6) and the necessity to increase $C_{0m(e)}$ by an order of magnitude (see (7)).

A possible mechanism of local increase of D_m (on L~2) could be resonant interactions of particles with quasi-periodic fluctuations of the geomagnetic field with the period of several minutes (Panasyuk, Sosnovets 1984). The amplitude of these fluctuations exceeds the regular spectrum of fluctuation power $D_m(\nu)$ with $p \approx 2$. Such oscillations of the geomagnetic field (which can be assigned to the $Pc\,3$ - $Pc\,4$ type) with periodicity of 8-10 min are observed practically continuously both in space and on-ground and are a typical phenomenon for magnetically quiet (K_p<2) periods. (see Fig. 9).

These data show that $P_m(\nu)$ can hardly be described by a single power law of the $P_m(\nu) \propto \nu^{-p}$ with $p \approx 2$ in the whole range of drift frequencies of RB particles.

The predominant spectral density at frequencies of several mHz (in comparison with that expected from the dependence $P_m(\nu) \propto \nu^{-2}$ should lead to an increase of D_m for the ion longitudinal drift period T_φ, corresponding to this frequency range.

Calculations of L_{jm} were made for protons near $L \approx 2$ (Panasyuk, Sosnovets (1984)). Protons with energies $E \approx 2$-5 MeV in this region have drift frequencies close to characteristic magnetosphere oscillation periods, mentioned above. Therefore the shift of L_{jm} to smaller L for this range of energies E in the inner zone of the RB could be caused by the presence of this type of predominant spectral components of the geomagnetic field power spectrum.

The results of quantitative analysis for this assumption are shown in Fig. 8. In the calculations the predominant harmonics were simulated using gaussians of different amplitude. According to this the C_{0m} constants of the different diffusion coefficients (2,3,4 in Fig.8), which exceed the typical C_{0m} value equal to $2 \cdot 10^{-14}$ s^{-1} (dashed line 1) of the magnetic diffusion coefficient $D_m = C_{0m} L^{10}$ were calculated. In concordance with these C_{0m} values the model dependencies of $L_{jm}(E)$ were calculated. Comparison with experimental data actually shows, that calculations of $L_{jm}(E)$ in concordance with D_m, defined by power spectra 2 and 3 is close to experimentally observed values of L_{jm} in the 2< E <30 MeV energy range for protons. Here an increase of D_m by a factor of 2-4 at frequencies of several mHz is observed in comparison to C_{0m} =$2 \cdot 10^{-14}$ s^{-1} typical for L >2.

However, this mechanism cannot be extended to protons with energies of tens and hundreds of MeV. In this energy range along with radial transport of particles from the RB boundary, there is a more efficient mechanism – particle injection due to decay of albedo neutrons usually called the CRAND mechanism (see section 1). Therefore, the deviations of experimental L_{jm} in the energy range of tens-hundreds MeV on L <2 from those predicted by the dependence $L_{jm} \propto E^s$ in the L >2 region could be associated with the CRAND mechanism. Actually, calculations of the proton belt structure in the inner RB zone, taking into account the CRAND mechanism (made by e.g. Beutier, et al. 1995), show satisfactory agreement with experimental data.

Above we analyzed the structure of the ion RB from the point of view of independently acting magnetic and electric diffusion. We will consider in more detail the issue of the relative contribution of these two types of particle transport.

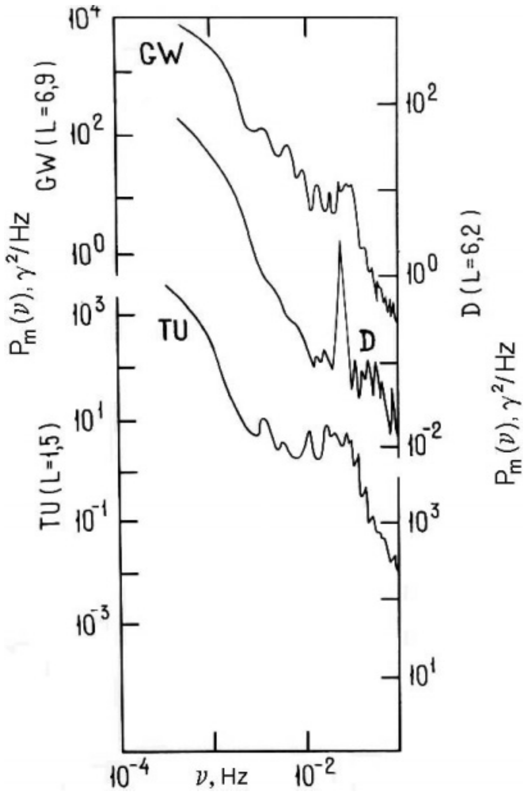

Figure 7. Power spectra of geomagnetic field fluctuations according to data of ground stations Thule (TU), Great Whale (GW) and the Dodge satellite in geostationary orbit.

Fig. 9 shows the experimental data on direct measurements of electric fields in the magnetosphere. These data actually support the model, which assumes electric field attenuation inside the plasmasphere. Basing on this fact we suggested an exponential form of the radial dependence:

$$P_e(\nu, L) = P_{0e}(L)\nu^{-l},$$

where

$$P_{0e}(L) = P_0 \exp(\beta \cdot L^{\alpha}) \quad (11)$$

Here coefficients P_0, α, and β were matched with direct experimental measurements of the power spectra of electric field fluctuations.

Using relation (11) the values of D_l were calculated for different slope indices $P_e(\nu) \propto \nu^{-l}$: l=0,1 and 2.

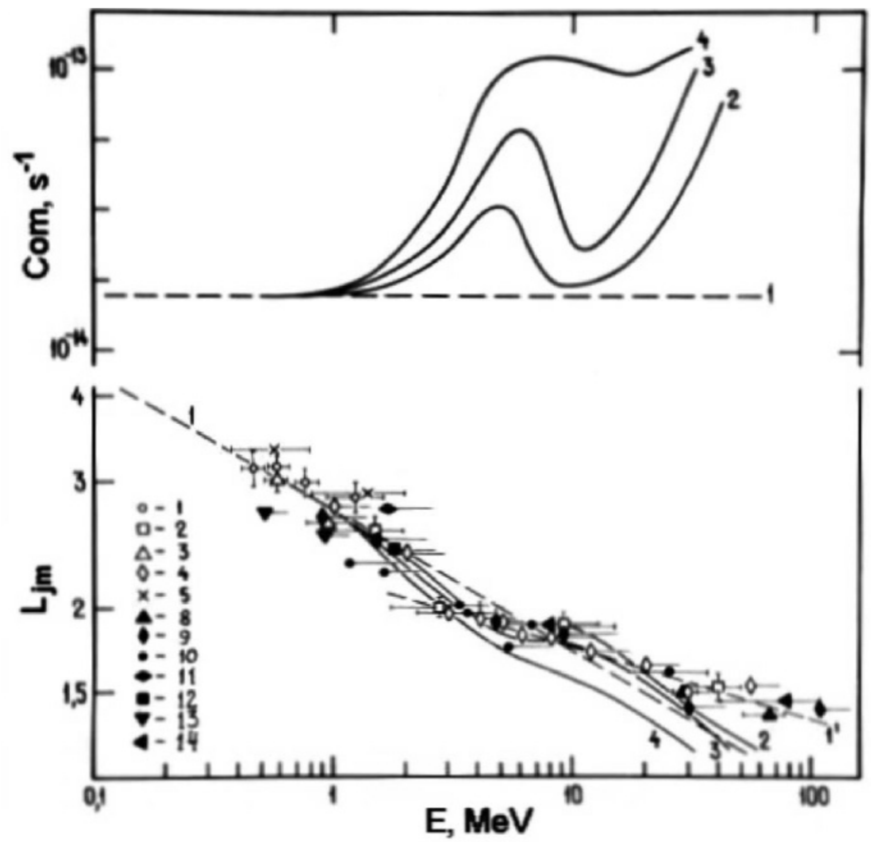

Figure 8. Simulation of the proton L_{jm} for different diffusion coefficients C_{0m} (1,2,3,4) with account for the predominant harmonics (see Fig. 7) of the geomagnetic field fluctuation spectrum.

Comparison of D_e and D_m=2·10^{-14}·L^{10} (the characteristic value for $K_p \leq 2 \div 3$) are shown in the lower part of Fig.9 in the form of a $(E/Q)_{me} = f(L)$ dependence, where E is in MeV.

The calculations presented above, show that magnetic diffusion should be the main transport mechanism in the RB at E/Q exceeding hundreds of keV/Q on 2<L<5. In the inner regions of the RB on L<2 the region of efficient electric diffusion can extend to energies exceeding several MeV/Q. A similar situation occurs on the outer L shells, where the region of efficient impact of electric diffusion can also reach several MeV/Q (for a harder fluctuation spectrum with l=1).

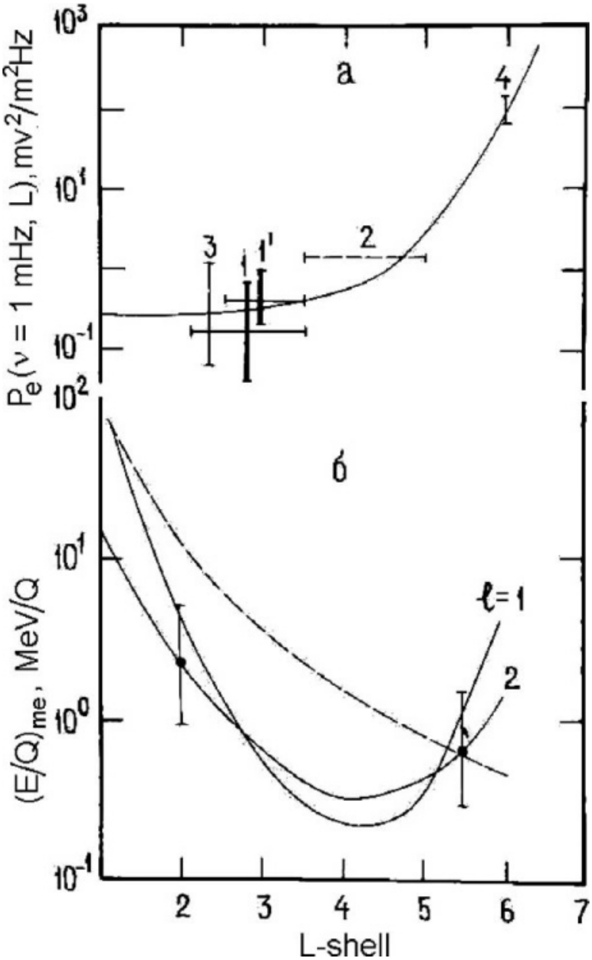

Figure 9. The upper panel shows the model dependence of the amplitude of the power spectrum for electric field fluctuations at ν =1 mHz versus L and comparison with direct experimental data (see text). Below we show the regions of predominant electric and magnetic diffusion for different values of the l parameter of the $P_e(\nu) \propto \nu^{-l}$ power spectrum

The physical meaning of the obtained result is that larger velocities of electric diffusion in the outer regions of the RB are achieved due to a relatively large value of the spectral density of electric field fluctuations in comparison to inner L-shells, therefore, here D_e exceeds D_m. With decreasing distance to the Earth $P_e(\nu, L)$ decreases displaying a plateau in the region of small L-shell values. However, since $D_e \propto L^6$, and

$D_m \propto L^{10}$, in the inner RB zone D_e once again approaches D_m and in the case of a hard fluctuation spectrum can exceed it. This could be the reason for the increase of particle transport velocity in the inner belt on L<2 for energies of several MeV/Q. And, consequently the shift of L_{jm} to L shells lower, than it could be expected for solely magnetic diffusion.

The analysis presented in this section corresponds to the space-energy structure of the ion RB, typical for magnetically quiet times, i.e. the stationary structure. Analysis of the particle dynamics in the RB lies outside the scope of this survey. However, it should be mentioned, that sometimes fast (pulse) injection of energetic ions into the RB is observed. This injection is associated with the influence of single powerful pulses of the magnetic and electric fields (SSC), which have specific form, and are associated with the arrival of a shock. For the first time this effect was observed on the CRRES satellite (Blake, et al.,1992) and was interpreted in the paper of Tverskoy (see Pavlov et al. (1993)). Such effects are very rare: since 1960 not more than 6 such effects have been reported (Loretzen et al., 2002).

4. CONCLUSIONS

1. Radial diffusion is the main transport mechanism for RB ions. Magnetic fluctuations play the main role in the formation of the space-energy distributions of RB particles. Fluctuations of the electric field can be responsible for the diffusion of low-energy particles (below 300 keV) in the outer zone of the RB, and, possibly play an important role in the inner zone. Obviously, the power spectrum of electrostatic field fluctuations is not flat, and is subject to attenuation inside the plasmasphere. Radial diffusion is a slow process. Rapid variations (on the scale of minutes) of the stationary ion RB structure, can be caused by powerful sudden pulses, which have a characteristic shape and are associated with the arrival of shocks from the Sun.
2. There are several sources of RB ions; among them galactic cosmic rays, solar and ionospheric plasma are the most important ones. Ionospheric plasma cannot be regarded an efficient source of particles with energies exceeding hundreds of keV inside the RB. For energetic RB ions (more than hundreds of keV) scaling of the energy distributions in E/Q is observed, where Q is the charge state of ions, typical for the interplanetary medium. This type of scaling differs from that of solar ions, which typically have a E/A representation.

5. ACKNOWLEDGEMENTS

The author would like to warmly thank the organizers of the NATO Advanced Research Workshop on Effects of Space Weather on Technology Infrastructure. The author is extremely grateful to Dr. Ioannis Daglis for providing the opportunity to participate in the ARW and to present this report. I also wish to thank Dr. Ekaterina Tolstaya for translation and editing this manuscript.

6. REFERENCES

Alfven H., Falthammar C-G., Cosmic Electrodynamics, Oxford, 1967.

Andrews M.K., Power density of equatorial electric field at L=2,3, J. Geophys. Res., 85, 1687-1694, 1980.

Baker D.N., Satellite anomalies due to space storms, in Space Storms and Space Weather Hazards, edited by I.A. Daglis, NATO Science series, 285-311, 2001.

Basilova R.N., Grigorov N.L., Kalinkin L.F., Excess fluxes of relativistic particles beneath the radiation belts, Cosmic Research, 11, 627-635, 1973 (in Russian).

Belyaev A.A., Koroteeva E.G., Panasyuk M.I., Modeling of oxygen ion spatial-energetic distributions in the Earth's radiation belts, Cosmic Research, 33, 322-325, 1995 (in Russian).

Biswas S., Durgaprasad N., Skylab measurements of low-energy cosmic rays, Space Sci. Rev., 25, 285-327, 1980.

Blake J.B., Friezen L.M., A technique to determine the charge states of the anomalous low-energy cosmic rays, Proc. 15th Intern. Cosmic Ray Conf., 2, 341-346, 1977.

Blake J.B., Kolasinski W.A., Fillins K.W., Mullen E.G., Injection of electrons and protons with energies of tens of MeV into L<3 on 24 March 1991, Geophys. Res. Letters, 19, 821-824, 1992.

Beutier T.D., Boscher D., France M., Salambo: A three dimensional simulation of the proton radiation belt, J. Geophys. Res. 100, 17181-17195, 1995.

Carpenter,D.L., Stone K., Siren J.C., Magnetospheric electric fields deduced from drifting whistler paths, J. Geophys Res., 77, 2819-2825, 1972.

Caufman D.P., Gurnett D.A., Satellite measurements of high latitude convection electric fields, Space Sci. Rev., 13, 369-392, 1972.

Cornwall J.M., Diffusion processes influenced by conjugate-point wave phenomena, Radio-Science, 3, 740-745, 1968.

Cornwall J.M., Transport and loss processes for magnetospheric helium, J. Geophys Res., 76, 264-267, 1971.

Cummings J.R., Mewaldt R.A., Selesnik R.S., Stone E.C., Blake J.B., Looper M.D., MAST observations of high energy trapped helium nuclei, EOS Trans., AGU, 75, 303, 1994.

Daglis I.A., Space storms, ring current and space-atmosphere coupling, in Space Storms and Space Weather Hazards, edited by I.A. Daglis, NATO Science Series, 1-42, 2001.

Falthammar C-G., Radial diffusion by violating of the third adiabatic invariant, in: Earth's particles and fields, edited by McCormac B.M., Reinhold Book Corp., v.4, pp.157-169, 1966.

Fritz T.A., Spjeldvik W.N., Observations of energetic radiation belt helium ions at the geomagnetic equator during quiet conditions, J. Geophys. Res., 83, 2579-2586, 1978

Fritz T.A., Feunell J.F., Zurbuchen T.H., Perry C., Grande M., Friedel R., Gloeckler G., Hefti S., Chen J., The use of iron charge state changes as a tracer for solar wind entry and energization, Ann. Geophysical, submitted in 2002.

Galperin Yu.I.., Gladyshev V. A.., Kuzmin A.K., Mullarschick T.M., Spatial inhomogenity of magnetosheath proton precipitation along the dayside cusp from the Arcad experiment, J. Geophys. Res., 85, 5105-5112, 1986.

Grigorov N.L., Kondrat'yeva M.A., Panasyuk M.I., Tretyakova Ch.A., Adams J.H., Blake J.B., Schultz M., Mewaldt R.A., Tylka A.J., Geophys. Res. Letters, 18, 1959-1962, 1991.

Gurnett D.A., Frank L.A., Observed relationship between electric fields and auroral particle precipitation, J. Geophys. Res., 78, 145-152, 1973.

Holthworth R.H., Mozer F.S., Direct evaluation of the radial diffusion coefficient near L=6 due to electric field fluctuations, J.Geophys. Res., 84, 2559-2566, 1979.

Hovestadt D., Gloeckler G., Evidences for solar wind origin of energetic heavy ions in the Earth's radiation belts, Geophys. Res. Lett., 5, 1055-1066, 1978.

Ilyin V.D., Ilyin I.V., Kuznetsov S.N., Stochastic instability of charged particles in the geomagnetic trap, Cosmic Research, 31, 75-86, 1986 (in Russian).

Kawashima N., Akai K., Murasato Y., Sasaki S., Electron beam emission from the EXO-5-B (Jikiken) satellite as a powerful diagnostic tool in the magnetosphere, Astrophysics and Space Sci., 106, 117-123, 1984.

Konradi A., Fritz T.A., Su S.Y., Time-averaged fluxes of heavy ions at the geostationary orbit, J. Geophys. Res., 85, 5149-5152, 1980.

Kovtyukh A.S., Dynamics of the main energetic spectra parameters of ionospheric and solar ions in the ring current and plasma sheet, Cosmic Research, 39, 24-33, 1999.

Kremser G., Studemann W., Wilken B., Gloeckler G., Average spatial distributions of energetic O^{+}, O^{2+}, O^{6+} and C^{6+} ions in the magnetosphere observed by AMPTE/CCE, J. Geophys. Res., 12, 847-850, 1989.

Kuznetsov S.N., Measurements of energetic ions at 500 km altitudes in the Earth's inner radiation belt. Izvestiya Akademii Nauk SSSR, 52, 821-823, 1988 .(in Russian).

Kuznetsov S.N., Nymmik R.A., Ryumin S.P., Yushkov B.Yu, Kudela K., Bucik R.,, Energetic charged particle fluxes under the radiation belts, Proc. 27th Int. Cosmic Ray Conf., 2, 329-333, 2002.

Lemaire J.F., From discovery of radiation belts to space weather perspectives, in Space Storms and Space Weather Hazards, edited by I.A. Daglis, NATO Science Series, 79-102, 2001.

Lorentzen I.R., Mazar J.E., Looper M.D., Feunell J.F., Blake J.B., Multisatellite observations of MeV ions injected during storms. J. Geophys. Res, A9, SMP 7-1-7-11, 2002

Mozer F.S., Power spectra of the magnetospheric electric field, J. Geophys. Res., 76, 3651-3658, 1971.

Mozer F.S., Lucht P., The average auroral zone electric field, J. Geophys. Res., 79, 3215-3220, 1974.

Panasyuk M.I., Reyzman S.Ya., Sosnovets E.N., Experimental results of α-particle measurements with energy more than 1 MeV/nucl., Cosmic Research, 15, 887-894, 1977. (in Russian).

Panasyuk M.I., Energetic ions of the solar origin in the radiation belts, Izvestiya Akademii Nauk SSSR, 47, 1850-1857, 1983 (in Russian).

Panasyuk M.I., Sosnovets E.N., Formation of proton radiation belts in the energy range of several MeV, Cosmic Res., 22, 756-762, 1984 (in Russian).

Panasyuk M.I., Experimental test of the transport mechanisms in the Earth's radiation belts, Cosmic Res., 22, 572-587, 1984 (in Russian).

Panasyuk M.I., Cosmic Ray and Radiation Hazards for Space Missions, in Space Storms and Space Weather Hazards, edited by I.A. Daglis, NATO Science series, 251-284, 2001.

Pavlov N.N., Tverskaya L.V., Tverskoy B.A., Chuchkov E.A., Variations of energetic particles of radiation belts during the strong magnetic storm on 24-26 March, 1991. Geomagnetism and Aeronomy, 33, 41-46, 1993 (in Russian).

Plyaskin V., Simulation of particle fluxes in the Earth's vicinity, Phys. Letters, B 516, 231-218, 2001.

Selesnik R.S., Mewaldt R.A., Cummings J.R., Multiply charged anomalous cosmic rays above 15 MeV/nucl, Proc. 25th Int. Cosmic Ray Conf., 2, 269-272, 1997.

Sibeck D., Ross K.S., McIntire R.W., Charge states of substorm particle injection, Geophys Res. Letters, 1283-1286, 1988.

Southwood D.J., Kaye S.M., Drift boundary approximation in simple magnetospheric convection models, J. Geophys. Res., 84, 5773-5779, 1979.

Spjeldvik W.N., Equilibrium structure of equatorial mirroring radiation belt protons, J. Geophys. Res., 9, 2801-2815, 1977.

Spjeldvik W.N., Fritz T.A., Theory for energy states of energetic oxygen ions in the Earth's radiation belts, J. Geophys. Res., 83, 1583-1598, 1978.

Tverskoy B.A., Dynamics of the Earth's Radiation belts, Geomagnetizm and Aeronomy, 4, 436-441, 1964.

Tverskoy B.A., Transport and acceleration of charged particles in the Earth's magnetosphere, Geomagnetizm and Aeronomy, 5, 793-798, 1965 (in Russian).

Tverskoy B.A., Electric fields in the magnetosphere and the origin of trapped particles, Solar Terrestrial Physics, 3, 297-317, 1970.

Van Allen J.A., The geomagnetically trapped corpuscular radiation, J.Geophys. Res., 64, 1683-1689, 1959.

Vernov S.N., Artificial satellite measurements of cosmic radiation. Doklady Akad. Nauk SSSR, 120, 1231-1233, 1958 (in Russian).

Volland H.A., A semiempirical model of large-scale megnetospheric electric field, J. Geophys. Res., 78, 171-178, 1973.