Earth's magnetotail as the reservoir of accelerated single- and multicharged ions replenishing radiation belts

E. I. Parkhomenko[1], M. I. Panasyuk[2], H. V. Malova[2,1], V.Yu. Popov[1,3,4], V. V. Kalegaev[2], N. A. Vlasova[2], L. M. Zelenyi[1]

[1] Space Research Institute of the Russian Academy of Sciences, Moscow, Russia
[2] Lomonosov Moscow State University, Scobeltsyn Institute of Nuclear Physics, Moscow, Russia
[3] Lomonosov Moscow State University, Physics Department, Moscow, Russia
[4] National Research University «Higher School of Economics», Moscow, Russia

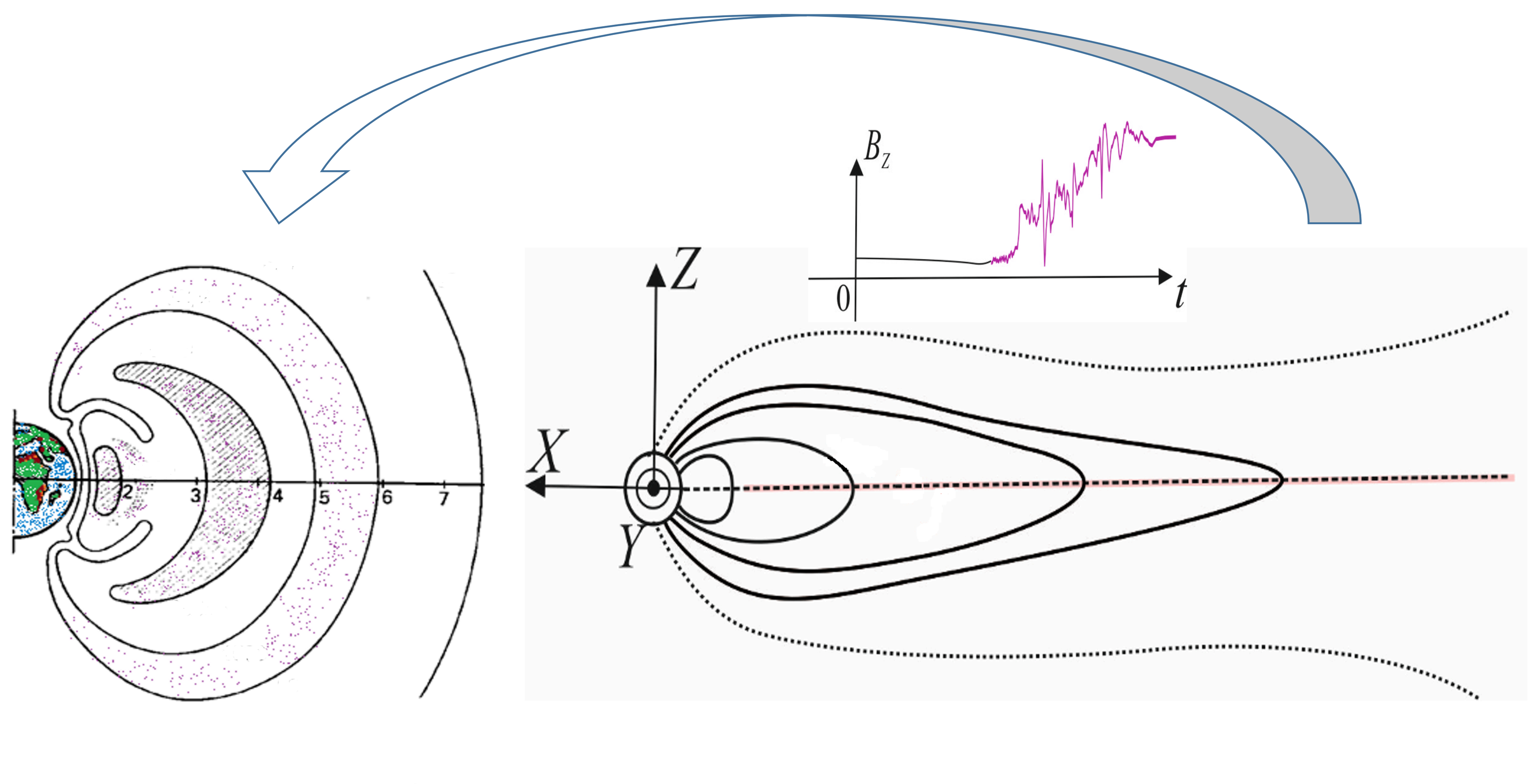
Space Research Institute

E-mail: jookove@mail.ru

Introduction

Numerous experimental and theoretical studies (e.g., Panasyuk, 1982, 1983; Hamilton et al., 1988; Kremser et al., 1987; Vlasova et al., 1988; Belyaev et al., 1995; Fennel et al., 1995; McDonald, 1998; Gkioulidou et al., 2015, 2016; Ukhorskiy et al., 2017; Turner et al., 2017; Allen et al. , 2016, 2017) made it possible to understand that the ion acceleration processes in the magnetotail play an important role in the formation of ion "injection spectrum" in the radiation belts. The measurements of the ion charge spectra, given in (e.g., Panasyuk, 1982,1983; Schulz, 1983; Hamilton et al., 1986; Kremser et al., 1987; Ukhorskiy et al., 2017; Turner et al., 2017; Allen et al., 2017), demonstrated the presence of particles of both ionospheric and solar origin in the ion composition of the magnetosphere. To date, the problem of mechanisms which are responsible for the transport and acceleration of ions from the tail of the Earth's magnetosphere to the ring current and proton radiation belts remains unsolved.
In this work we are studying substorm acceleration of multi-charged oxygen ions as the source of ring current replenishment by energetic ion population.

- **AMPTE/CCE** (e.g., Gloeckler et al., 1985)
- **AMPTE/IRM** (e.g., Gloeckler et al., 1985a)
- **Molniya-2, Explorer 45, ATS-6, ISEE- 1** (e.g., Panasyuk, 1982)



$-4.5 < X < -7.5\ R_E$

Numerical Model

In this work we are studying substorm acceleration of multi-charged oxygen ions as the source of ring current replenishment by energetic ion population. We present a numerical model that allows evaluating the acceleration of oxygen ions O^{+}-O^{+8} in the course of two possible perturbation processes:

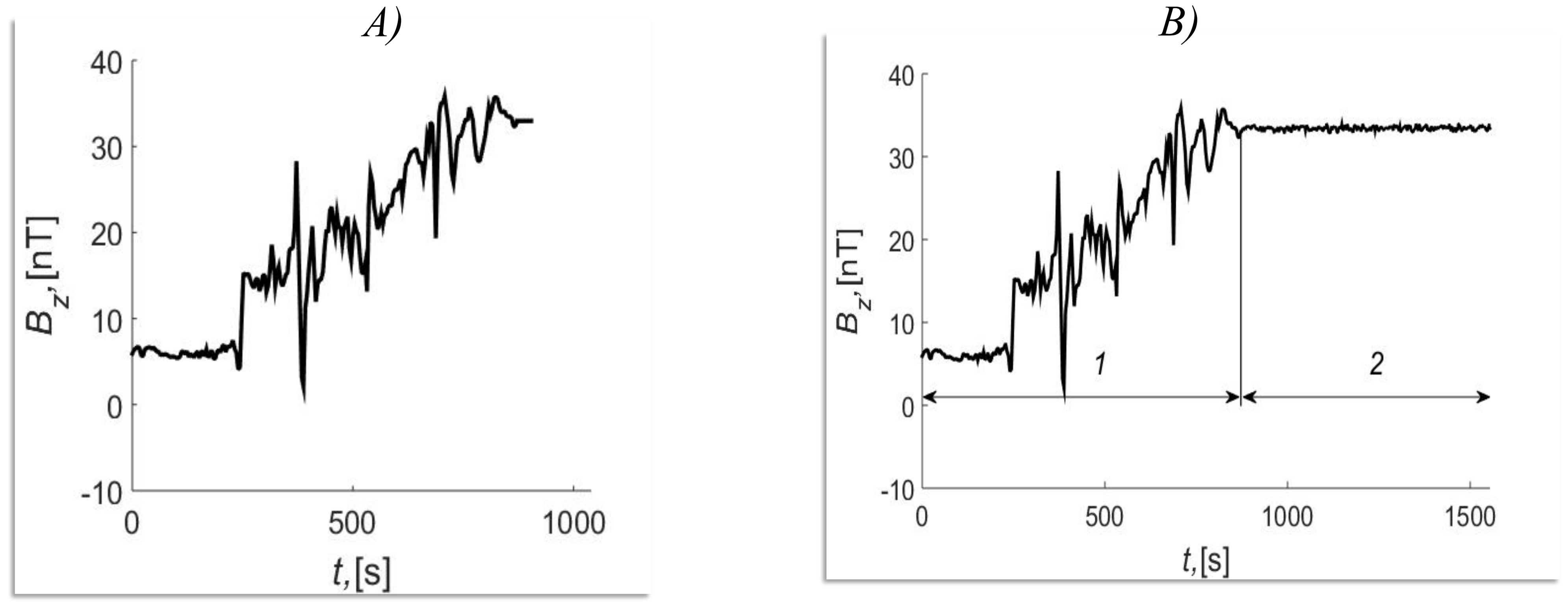


Figure 1. A) Profile of the normal magnetic field component of dipolarization over time interval $\Delta t \approx 13$ min, which includes multiple DFs observed at time scale $t_{DFs} \approx 20$ s by Clusters. B) The dipolarization (1) is followed by subsequent electromagnetic wavy activity (2).

The total magnetic and electric fields is considered as a superposition of following components:

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_0 + \Delta\mathbf{B}_{\mathrm{Df}}(t) + \delta\mathbf{B}(\mathbf{r},t)$$

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 + \Delta\mathbf{E}_{\mathrm{Df}}(t) + \delta\mathbf{E}(\mathbf{r},t)$$

Here $\mathbf{B}_0$, $\mathbf{E}_0$ are correspondingly magnetic and electric fields in the basic current sheet model; $\Delta\mathbf{B}_{\mathrm{Df}}(t)$, $\Delta\mathbf{E}_{\mathrm{Df}}(t)$ –is the magnetic and electric fields of multiple dipolarization fronts, corresponding to the Cluster's observations on July 20, 2013 from 01:33:08 to 01:48:11 UT; $\delta\mathbf{B}(\mathbf{r},t)$ is the oscillating field produced by magnetic fluctuations, which depends on spatial coordinates $\mathbf{r}$ and time t. Components of the induction electric field $\delta\mathbf{E}(\mathbf{r},t)$ were found by solving Maxwell equations. Initial phases $\varphi^1_{\mathbf{k}}$, $\varphi^2_{\mathbf{k}}$ and wave number k are distributed uniformly on $[0, 2\pi]$ and $\frac{2\pi}{L}\cdot[0.05, 4]$.

The magnetic $\delta\mathbf{B}(\mathbf{r},t)$ and electric $\delta\mathbf{E}(\mathbf{r},t)$ components of fluctuations:

$$\delta B_x(\mathbf{r},t) = \sum_{\boldsymbol{k}} \delta B(\mathbf{k}) \frac{k_\perp}{k} g_{\boldsymbol{k}}(\mathbf{r},t)$$

$$\delta B_y(\mathbf{r},t) = \sum_{\boldsymbol{k}} \delta B(\mathbf{k}) \left(\frac{k_y k_x}{k_\perp k} g_{\boldsymbol{k}}(\mathbf{r},t) + \frac{k_z}{k_\perp} h_{\boldsymbol{k}}(\mathbf{r},t)\right)$$

$$\delta B_z(\mathbf{r},t) = \sum_{\boldsymbol{k}} \delta B(\mathbf{k}) \left(\frac{-k_z k_x}{k_\perp k} g_{\boldsymbol{k}}(\mathbf{r},t) - \frac{k_y}{k_\perp} h_{\boldsymbol{k}}(\mathbf{r},t)\right)$$

$$\delta E_x(\mathbf{r},t) = \frac{\omega_{\boldsymbol{k}}}{c} \sum_{\boldsymbol{k}} \delta E(\mathbf{k}) \frac{1}{2k_\perp} g_{\boldsymbol{k}}(\mathbf{r},t)$$

$$\delta E_y(\mathbf{r},t) = \frac{\omega_{\boldsymbol{k}}}{c} \sum_{\boldsymbol{k}} \delta E(\mathbf{k}) \left(-\frac{k_z}{2k_x k_\perp} g_{\boldsymbol{k}}(\mathbf{r},t) - \frac{k_y}{2k_x k_\perp} h_{\boldsymbol{k}}(\mathbf{r},t)\right)$$

$$\delta E_z(\mathbf{r},t) = \frac{\omega_{\boldsymbol{k}}}{c} \sum_{\boldsymbol{k}} \delta E(\mathbf{k}) \left(\frac{k_y}{k_\perp k} g_{\boldsymbol{k}}(\mathbf{r},t) - \frac{k_z}{2k_x k_\perp} h_{\boldsymbol{k}}(\mathbf{r},t)\right)$$

Test Particle Simulation

$N = 5\cdot10^5$ particles were injected inside a box having the following *3-D* boundaries:

$x \in [-L_{x1}, -L_{x2}]$, $y \in [-L_{y1}, L_{y2}]$, $z \in [-L_z, L_z]$

$L_{y1} = -L_{y2} = 13\cdot10^4$ km ; $L_{x1} = 10^5$ км ; $L_{x2} = 6\cdot10^4$ km;

$L_z = 10\cdot L_{z0} = 2\cdot10^4$ km

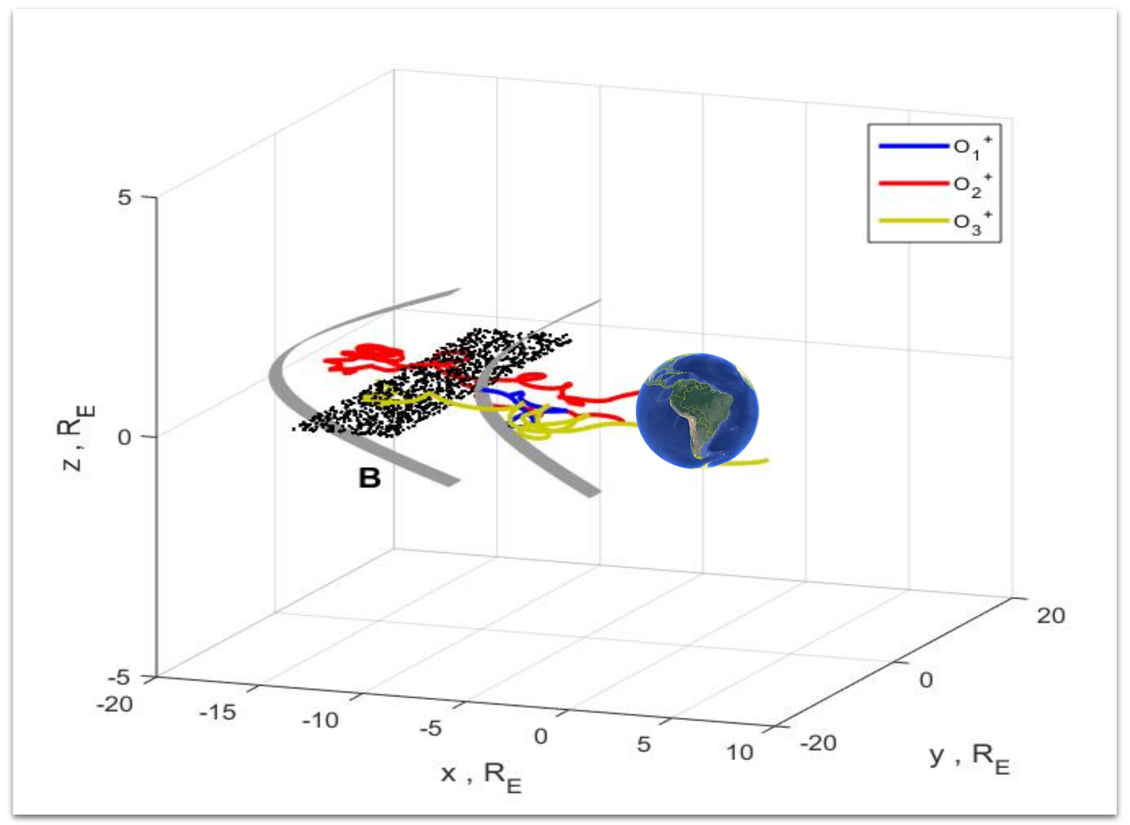


***Figure 2.** The basic structure of current sheet model. The magnetic field lines of force are shown by thick solid lines. The initial positions of particles (a set of points on the plane) and the trajectories of test particles-oxygen ions O^{+}- O^{+3} are shown.*

The initial particle velocity distribution has the form of a shifted kappa distribution :

$$f(\mathbf{v}) = \frac{n_0 A_{\kappa_\varepsilon}}{2\left(\sqrt{\pi k} V_{\kappa_\varepsilon}\right)^3} \cdot \sum_{s=1,2} 1 + \frac{\mathbf{v}_\perp^2 + (\mathbf{v}_\parallel - (-1)^s \mathbf{v}_{\mathrm{D}})^2}{\kappa_\varepsilon \cdot v_{\kappa_\varepsilon}^2}^{-(\kappa_\varepsilon+1)}$$

where n_0 is plasma density; $v_{\kappa_\varepsilon} = v_T\sqrt{2 - \frac{3}{\kappa_\varepsilon}}$ is normalized thermal velocity; $\kappa_\varepsilon = 3$ is the kappa-function parameter; $\mathbf{v}_{\mathrm{D}} = 1400\ \frac{\mathrm{km}}{\mathrm{s}}$ is the particle drift velocity; $\mathbf{v}_\parallel$, $\mathbf{v}_\perp$ are ,respectively, the parallel and perpendicular components of particle velocities.

Earth's magnetotail as the reservoir of accelerated single- and multicharged ions replenishing radiation belts

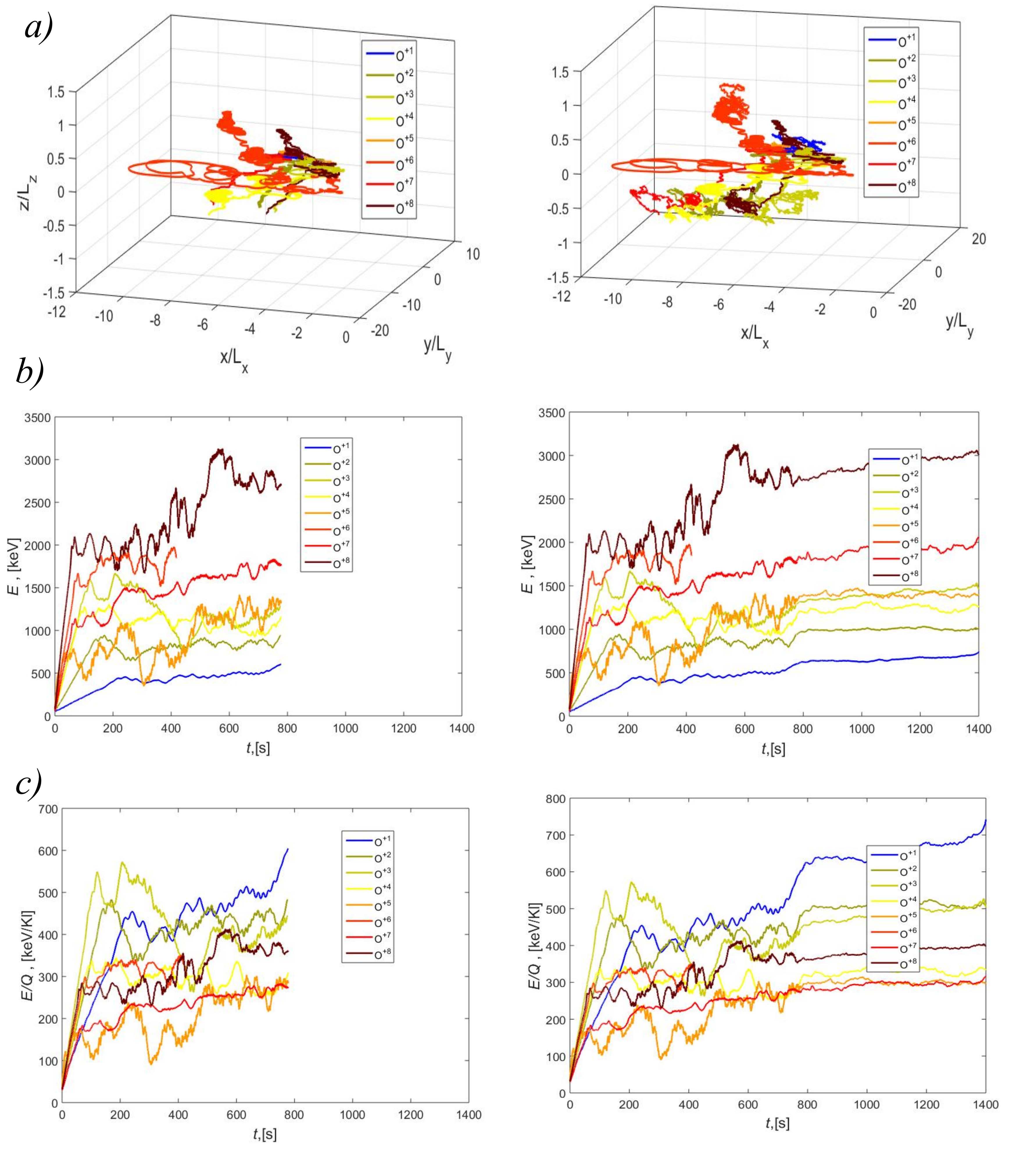
E. I. Parkhomenko[1], M. I. Panasyuk[2], H. V. Malova[2,1], V.Yu. Popov[1,3,4], V. V. Kalegaev[2], N. A. Vlasova[2], L. M. Zelenyi[1]

[1] Space Research Institute of the Russian Academy of Sciences, Moscow, Russia
[2] Lomonosov Moscow State University, Scobeltsyn Institute of Nuclear Physics, Moscow, Russia
[3] Lomonosov Moscow State University, Physics Department, Moscow, Russia
[4] National Research University «Higher School of Economics», Moscow, Russia

Space Research Institute

E-mail: jookove@mail.ru

Results



Figures 3-4.*Characteristic trajectories of oxygen ions (a) and corresponding energy gains of these particles during magnetic dipolarizations (scenario A-B). Temporal variation of energies of oxygen ions O^{+}-$O^{+8}$are presented in dimensional form (fig.3,4b) and normalized to charge numbers Q (fig.3,4c).*

Figures 3 and 4 describes characteristic particle trajectories (panel (a) at both figures); energy gains (panel (b) at both figures) and energy gains of each kind of particles normalized to particle charges (panel (c) at both figures) in scenario of acceleration A and B, correspondingly.

Figures 5, *a*, *b* illustrate energy spectra of oxygen ions O^{+}-O^{+8}, that were traced inside the model box with the same initial conditions, but different initial densities n_0 (e. g., Kremester et al., 1987; Turner et al., 2017). Experimental spectra (pink dotted lines) were obtained by digitizing *Figure 2* taken from (Fennell et al., 1996) and given according to the CRRESMICS experimental data and averaged over the range of *L*-shells in the diapason $4.5 < L < 7.5$. Tables 1–2 present the values of initial average energies $\overline{E}_0$, maximum energies E_{max} and ratio of maximum energies to charge number E_{max}/Q of particles in current sheet, where the following scenarios were considered: (A) multiple dipolarization fronts (Table 1); (B) multiple dipolarization fronts with subsequent electromagnetic fluctuations (Table 2).

Table 1

Q	$\overline{E}_0$, [keV]	E_{max}/Q, [keV/i]	E_{max}, [keV]
8	12	875	**7000**
7	12	940	**6600**
6	12	980	**5900**
5	12	1020	**5100**
4	12	1100	**4400**
3	12	1260	**3800**
2	12	1450	**2900**
1	12	1700	**1700**

Table 2

Q	$\overline{E}_0$, [keV]	E_{max}/Q, [keV/i]	E_{max}, [keV]
8	12	920	**7400**
7	12	1000	**7000**
6	12	1040	**6250**
5	12	1070	**5370**
4	12	1162	**4650**
3	12	1350	**4050**
2	12	1550	**3100**
1	12	1900	**1900**

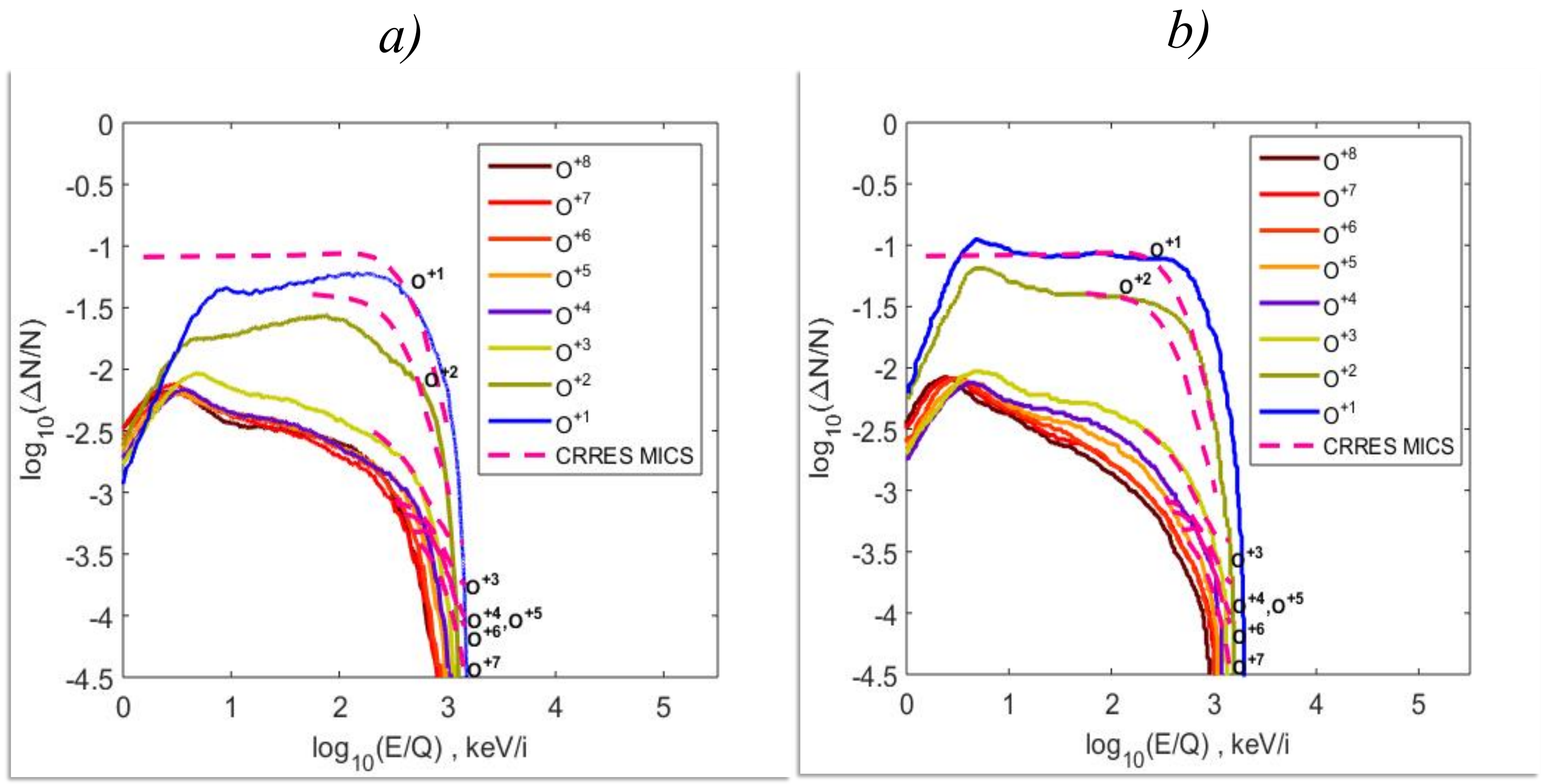


Figure 5. *Energy distributions normalized to charge numbers E/Q of accelerated oxygen ions O^{+}- O^{+8} during (a) interaction with multiple dipolarization fronts; (b) interaction with multiple dipolarization fronts and subsequent of electromagnetic fluctuations.*

Conclusions

- It is shown that magnetic substorms can be possible sources of replenishment of the ring current and radiation belts in the Earth's magnetosphere.
- It is shown that the multiscale changes of magnetic fields lead to the generation of induced electric fields that interact with oxygen ions in a resonant manner, that is, the higher the charge number Q the more effective the transfer of energy from fields to particles (Table 1,2). We have shown the invariance of the energy gain for O^{+}-O^{+8} ions in E /Q representation in the low-energy region (<150 keV), which is a consequence of particle transport by a large-scale electric field.
- Taking into account the agreement between the experimental and model energy spectra for ions O^{+}-O^{+2} in case (A), it can be assumed that these particles could reach the Earth's radiation belts during particle acceleration on dipolarization fronts in the magnetotail.
- The taking into account large-scale electromagnetic wave activity accompanying usually magnetic substorms allows to explain the shape of ions O^{+3}-O^{+8} spectra and it is another confirmation of the idea of a close connection of different magnetospheric regions as the magnetotail and the ring current with radiation belts, developed in this work.