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

### 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; Ukhorvsky 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; Ukhorvsky et al., 2017; Turner et al., 2017; Allen et al., 2017), demonstrated the presence of particles of both isospheric 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.

### 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 $O^{+}–O^{6+}$ in the course of two possible perturbation processes:

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

   \[ \mathbf{B}(r, t) = \mathbf{B}_0 + \Delta \mathbf{B}(r, t) + \delta \mathbf{B}(r, t) \]
   \[ \mathbf{E}(r, t) = \mathbf{E}_0 + \Delta \mathbf{E}(r, t) + \delta \mathbf{E}(r, t) \]

   Here $\mathbf{B}_0, \mathbf{E}_0$ are correspondingly magnetic and electric fields in the basic current sheet model; $\Delta \mathbf{B}(r, t), \Delta \mathbf{E}(r, t)$ – 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; $\delta \mathbf{B}(r, t)$ is the oscillating field produced by magnetic fluctuations, which depends on spatial coordinates $r$ and time $t$. Components of the induction electric field $\delta \mathbf{E}(r, t)$ were found by solving Maxwell equations. Initial phases $\varphi^B_0, \varphi^E_0$ and wave number $k$ are distributed uniformly on $[0, 2\pi]$ and $k^2 = k_x^2 + k_y^2 + k_z^2$. The magnetic $\delta \mathbf{B}(r, t)$ and electric $\delta \mathbf{E}(r, t)$ components of fluctuations:

   \[ \delta \mathbf{B}_x(r, t) = \sum \delta B(k, k) \frac{k_x}{k} g_x(r, t) \]
   \[ \delta \mathbf{B}_y(r, t) = \sum \delta B(k, k) \frac{k_y}{k} g_y(r, t) \]
   \[ \delta \mathbf{B}_z(r, t) = \sum \delta B(k, k) \frac{k_z}{k} g_z(r, t) \]
   \[ \delta \mathbf{E}_x(r, t) = \frac{\alpha_k}{c} \sum \delta E(k) \frac{1}{2k^2} g_x(r, t) \]
   \[ \delta \mathbf{E}_y(r, t) = \frac{\alpha_k}{c} \sum \delta E(k) \frac{k_y}{2k^2} g_y(r, t) \]
   \[ \delta \mathbf{E}_z(r, t) = \frac{\alpha_k}{c} \sum \delta E(k) \frac{k_z}{2k^2} g_z(r, t) \]

2. 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 $t_{DF} = 20$ s by Clusters. B) The dipolarization ($\mathbf{I}$) is followed by subsequent electromagnetic wave activity ($\mathbf{2}$).

3. The test particle simulation (TPS) method is a powerful tool to study the entire processes of particle transport and acceleration. The fundamental equations of motion for test particles are the Newtonian equations of motion:

   \[ m \frac{d^2 \mathbf{r}}{dt^2} = \mathbf{F}_{\text{total}}(\mathbf{r}, \mathbf{v}, t) \]

   where $m$ is the mass of the test particle, $\mathbf{r}$ and $\mathbf{v}$ are its position and velocity vectors, and $t$ is time. The total force acting on the test particle includes the magnetic field force $\mathbf{F}_{\text{mag}}$, the electric field force $\mathbf{F}_{\text{elec}}$, and the ion drag force $\mathbf{F}_{\text{drag}}$:

   \[ \mathbf{F}_{\text{total}} = \mathbf{F}_{\text{mag}} + \mathbf{F}_{\text{elec}} + \mathbf{F}_{\text{drag}} \]

   The magnetic force is given by the Lorentz force:

   \[ \mathbf{F}_{\text{mag}} = q \mathbf{v} \times \mathbf{B} \]

   where $q$ is the charge of the test particle, $\mathbf{v}$ is its velocity, and $\mathbf{B}$ is the magnetic field.

   The electric force is:

   \[ \mathbf{F}_{\text{elec}} = q \mathbf{E} \]

   where $\mathbf{E}$ is the electric field.

   The ion drag force is:

   \[ \mathbf{F}_{\text{drag}} = -6 \pi \eta R \mathbf{v} \]

   where $\eta$ is the drag constant, $R$ is the particle radius, and $\mathbf{v}$ is the particle velocity.

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

   \[ f(v) = \frac{n_p \nu_p}{(\nu_p - 1)\nu_p^2} \left( \frac{\nu_p - 1}{\nu_p} \right)^{\nu_p} \left( \frac{v}{\nu_p} \right)^{\nu_p - 1} \exp \left( \frac{-v^2}{\nu_p} \right) \]

   where $n_p$ is plasma density; $\nu_p = \nu_p - \frac{2}{\kappa} + 1$ is normalized thermal velocity; $\kappa = 3$ is the kappa-function parameter; $\nu_p = 1400 \, \text{km/s}$ is the particle drift velocity; $\nu_p, \nu_p$ are respectively, the parallel and perpendicular components of particle velocities.

### Test Particle Simulation

N $\sim 10^5$ particles were injected inside a box having the following $E-D$ boundaries:

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

$L_{x1} = -L_{x2} = 13 \times 10^6 \text{ km}; L_{y1} = 10^6 \text{ km}; L_{y2} = 6 \times 10^4 \text{ km};
L_z = 10 \times L_{0}$

$L_{x1} = 2 \times 10^4 \text{ km}$

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 $O^+–O^{6+}$ are shown.
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Results

Figures 3 and 4 describe 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⁻\textsuperscript{−} - O\textsuperscript{8+}, that were traced inside the model box with the same initial conditions, but different initial densities n\textsubscript{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 CRRES/MCS 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 E\textsubscript{0}, maximum energies E\textsubscript{max} and ratio of maximum energies to charge number E\textsubscript{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

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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⁻\textsuperscript{−} - O\textsuperscript{8+} are presented in dimensional form (fig.3,4b) and normalized to charge numbers Q (fig.3,4c).

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⁻\textsuperscript{−} - O\textsuperscript{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⁻\textsuperscript{−} - O\textsuperscript{8+} 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⁻\textsuperscript{−} - O\textsuperscript{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.

E. I. Parkhomenko\textsuperscript{1}, M. I. Panasyuk\textsuperscript{2}, H. V. Malova\textsuperscript{2,1}, V.Yu. Popov\textsuperscript{1,3,4}, V. V. Kalegnaev\textsuperscript{1}, N. A. Vlasova\textsuperscript{2}, L. M. Zelenyi\textsuperscript{1}

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

E-mail: jokkeve@mail.ru