Earth magnetic field as analyzer of the cosmic ray ion charge in MONICA experiment

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Abstract. The future onboard experiment MONICA (monitor of cosmic ray nuclei and ions) is aimed for studying the cosmic ray ion fluxes from H to Ni in the energy range 10-300 MeV/n in vicinity of Earth. Its main scientific objective is the measurement of ionization states, as well as elemental, isotope composition and energy spectra of Solar Energetic Particle (SEP) fluxes. The method of the ionization state measurement based on the usage of Earth magnetic field as a separator of particle charge will be utilized in this experiment. The present contribution is dedicated to investigate the possibilities and features of this method for the MONICA experiment. The real time dependences of inverse square of cut-off geomagnetic L-shell \( L_{\mathrm{c}}^{-2} \) on magnetic rigidity \( R \) in rigidity range 640-2780 MV were studied experimentally during powerful SEP events December 13-15 2006. The possibility to simulate these dependences using the modern geomagnetic field models is analyzed as well.

1. Introduction

New onboard experiment MONICA is aimed for studying the cosmic ray ion fluxes from H to Ni in the energy range 10-300 MeV/n in vicinity of Earth [1]. The experiment’s main scientific objective is the measurement of ion charge states, as well as elemental and isotope composition and energy spectra of SEP fluxes for individual solar events and to study the evolution of these characteristics over time. At the same time MONICA will investigate ionization states and isotope composition of anomalous and galactic cosmic rays.

Ion charge states of SEP observed in near-Earth space are considered to be sensitive probes for conditions in acceleration region, such as, particle acceleration dynamics, solar plasma mean electron density and temperature [2, 3]. The ionization state of iron ions is the most informative and sensitive indicator for these processes [4]. It is known that the mean ionization state of iron ions with energies more then 10 MeV/n is about \( Q=+14 \) for “gradual” SEP events and more then \( Q=+20 \) for “impulsive” events [5, 6]. Thus, Fe mean charge state can be used for identification of SEP event type.

The investigations will be carried out with high-acceptance multilayer silicon telescope-spectrometer MONICA installed onboard satellite which will be launched into low Earth polar orbit with altitude about 600 km [1]. Instrument will be pointed to zenith. The spectrometer will detect nuclei in energy ranges: H and He – from 7 to 70 MeV/n, CNO group – from 10 to 150 MeV/n, Fe group – from 15 to 300 MeV/n. Instrument will measure nuclear charge (Z), mass, energy, and incident angle for each detected particle. The identification of registered nuclei will be implemented by modified \( \Delta E-E \) method [7]. Spectrometer acceptance is about 100 cm\(^2\)sr, the field of view is ±45°.
In MONICA experiment the method of ion charge (Q) measurement based on the usage of Earth magnetic field as a particle charge separator will be realized. This method is unique for investigated energy range of ions. The direct measurement of charge state of cosmic ray ions with energies more than several MeV/n is impossible. The ions with initial charge state Q and energy >10 MeV/n that enter into the spectrometer will be stripped of orbital electrons within several µg/cm² of the instrument material, i.e. really inside the thin kapton windows installed above the first silicon detector of multilayer spectrometer. The ion stripping cross sections can be found in [8].

This contribution is dedicated to study the possibility and features of using Earth magnetic field as a separator of charge states of cosmic ray ions with energies from about 10 MeV/n up to several hundreds MeV/n for the MONICA experiment.

2. Method of ion charge measurement

Today the direct SEP ion charge measurements were carried out only for ions with energies less than 5 MeV/n. The electrostatic ion charge analyzers were used for these measurements (for example, ULEZEQ onboard ISEE-1, ISEE-3 [9] and SEPICA onboard ACE [10]). As a rule, these sensors combine the determination of the electrostatic deflection of incoming ions in a collimator-analyzer assembly by the measurement of the impact position on the detector plane and a dE/dx - E telescope. A direct measurement of the charge state is impossible for ions with energies more than 10 MeV/n because of the required electric field strength has to be unrealistic high and the analyzer acceptance has to be unrealistic large.

The unique method for the measurement of ion charge states for energies more than 10 MeV/n is using of Earth magnetic field as a separator.

It is well known that penetration depth of ions into the magnetosphere depends on their gyro radius. On a polar-orbiting satellite with zenith-pointing charge particle detector onboard, moving from a pole to the equator, this can be observed as a flux cut-off for particles with given magnetic rigidity \( R \) at a corresponding magnetic L-shell \( L_C \). This effect is depicted in Fig. 1. This figure shows the dependence of registration efficiency \( \text{Eff}(\Delta E) \) for ions detected by instrument, moving from the geomagnetic equator to pole, in energy range \( \Delta E \) on L-shell. This efficiency is defined as the ratio of number of ions detected inside the magnetosphere \( N_{\text{in}}(\Delta E) \) to their number detected outside it in interplanetary space \( N_{\text{out}}(\Delta E) \).

\[
\text{Eff} = \frac{N_{\text{in}}}{N_{\text{out}}}
\]

As it was assumed in [4], for the real magnetosphere the inverse square of this cut-off L-shell value \( L_C \) linearly depends on the particle rigidity \( R \):

\[
L_C \propto \frac{1}{R^2}
\]
This dependence can be used to determine the mean charge of the particles \( Q \):

\[
\frac{1}{L_c^2} = aR + b \,.
\]

where \( E, M=m_0c^2 \) and \( P=pc \) are the measured ion kinetic energy, the mass at rest and momentum in energy units (eV) correspondingly.

The main features of the method described above are:

1) The high statistics of detected ions is needed for the reconstruction of mean ion charge, and therefore the high-acceptance spectrometer is required.

2) It is necessary to know the geomagnetic cut-off rigidity in real time (i.e. \( a \) and \( b \) values), as Earth magnetosphere is distorted very often especially during SEP events.

The method of geomagnetic separator was successfully tested in SAMPEX experiment [4] for the solar events of October 30 - November 7, 1992. The mean values of ion charge of helium, carbon, oxygen, neon, magnesium and iron in the energy range 0.3-70 MeV/n were obtained. However, for ion energies more than 70 MeV/n, this method has not been experimentally tested.

In order to check the possibility of separator method using for MONICA energy range 10-300 MeV/n the following investigations have been carried out: 1) experimental study of real-time \( 1/L_c^2(R) \) dependences in the rigidity range corresponding to the energy interval of iron ions (the most informative solar energetic ions) detected by MONICA; 2) analysis of possibility to simulate real-time \( 1/L_c^2(R) \) dependences using the modern geomagnetic field models.

The rigidity interval of Fe ions (mean ionization state \( Q(Fe)=+14 \)) detected by MONICA is 670-3230 MV during “gradual” SEP events and it is 470-2260 MV during “impulsive” events (mean ionization state \( Q(Fe)=+20 \)). Since cut-off L-shell \( L_c \) depends on ion rigidity \( R \) only the proton (i.e., hydrogen ions with known charge \( Q(H)=+1 \)) flux in the energy range 200-2000 MeV (corresponding to the rigidity interval 640-2780 MV) registered by PAMELA spectrometer [11] during SEP events on December 13-15, 2006 have been used for the study of real-time \( 1/L_c^2(R) \) dependences.

3. Experimental study of \( 1/L_c^2(R) \) dependence during the solar events with PAMELA data

Experimental study of the \( 1/L_c^2(R) \) dependence was carried out with the PAMELA experiment data [11]. PAMELA experiment is developed for investigation of cosmic ray antiproton, proton, positron, electron and nuclei fluxes in a wide energy range. Energy range of detected protons is 80 MeV - 700 GeV. The experiment has been carrying out since 15 June 2006 until the present time onboard of the Resurs DK1 satellite. Its orbit is elliptical and semi-polar with an inclination 70.4° and an altitude varying between 350 and 650 km. Magnetic spectrometer PAMELA has a field of view of \( \pm 20^\circ \) and geometrical factor of 21 cm\(^2\)sr. The instrument is pointing to zenith. The detailed description of instrument is given in [11].

To study the geomagnetic cut-off rigidity the proton counting rates obtained by PAMELA during the powerful SEP events 13-15 December 2006 were used. This Solar event provided the necessary high statistics of detected protons for reconstruction of \( 1/L_c^2(R) \) dependencies and allowed to study particle penetration into the Earth’s magnetosphere under different levels of disturbance.

In Fig. 2 (top panel) the dependence of the proton counting rate detected by PAMELA instrument is shown, as well as the integral proton flux measured by the GOES-11 satellite versus time during the period of December 13-15 2006. The same figure (bottom panel) illustrates the dependences of \( D_{st} \) index, interplanetary magnetic field components \( B_x, B_y \) in GSM coordinates and dynamical pressure of solar wind \( P_{dyn} \) over time. As it can be seen from the graphs, these powerful SEP events were accompanied by a severe geomagnetic storm with maximum \( D_{st} \) variation of \(-150 \) nT that occurred at
the end of the day December 14 when CME-driven interplanetary shock impacted on the Earth's magnetosphere. Time profile of PAMELA proton counting rate in the polar caps (peaks in counting rate in Fig. 2) qualitatively reproduces the proton flux profile obtained by GOES-11. Due to the PAMELA memory overflow the experimental data for about a day after the beginning of SEP event were lost.

The counting rate of protons in the six energy bins: \(200-300\), \(300-500\), \(500-700\), \(700-1000\), \(1000-1400\), \(1400-2000\) MeV for the reconstruction of \(1/L_C^2 (R)\) experimental curves were analyzed. The selection of these bins is defined by the SEP proton spectrum. For example, the SEP proton spectrum observed during the crossing of North polar cap at the SEP event beginning on 13.12.2006 is presented in Fig. 3. Galactic proton spectrum obtained for solar quiet period in December 2006 is also entered in the figure. The graph shows that at energies up to 2 GeV SEP protons dominate, while above 2 GeV GCR protons do. PAMELA counting rate of protons with energy more than 2 GeV is too low for our analysis. Hence the upper boundary of 2 GeV for the studied energy range was defined. The lower boundary of 200 MeV was chosen being corresponded to the minimum proton energy when the PAMELA instrument detection efficiency increases up to 1.

**Figure 2.** First (from top) graph: counting rate of protons detected by PAMELA instrument and integral proton flux for \(E>100\) MeV measured by GOES-11 vs. time. Second graph: \(D_ST\) index vs. time. Third graph: interplanetary magnetic field components \(B_y\), \(B_z\) in GSM coordinate system vs. time. Fourth graph: dynamical pressure of solar wind \(P_{\text{dyn}}\) vs. time.

**Figure 3.** SEP proton spectrum observed by PAMELA during the crossing of polar cap at the SEP event beginning (red) and GCR proton spectrum for solar quiet period in December 2006 (black).
The experimental values of geomagnetic cut-off L-shell \( L_C \) were determined from obtained dependences of the proton detection efficiency in the Earth magnetosphere (\( Eff \)) on the L-shell (see Fig. 4). These dependencies on the L-shell were approximated by Boltzmann function:

\[
Eff = \frac{A_1 - A_2}{1 + e^{(L - L_C)/\Delta L}} + A_2,
\]

where \( A_1 \) and \( A_2 \) are the levels of the lower and upper plateaus (in this case 0 and 1 respectively), \( L_C \) - inflection point at half height, \( \Delta L \) - transition distance from \( A_1 \) to \( A_2 \). To determine the mean rigidities \( R \) for the six selected energy intervals the proton spectra obtained in the polar caps were taken into account.

In Fig. 5 the experimental \( 1/L_C^2(R) \) dependence for run 03:59–04:04 UT 13.12.2006 is presented. As it can be seen from the plot, the dependence is practically linear in the studied range of rigidities 640-2780 MV. Dependences for all other runs have the similar shapes. As a result all experimental \( 1/L_C^2(R) \) dependences were approximated by linear functions: \( 1/L_C^2(R) = a \cdot R + b \). Table 1 shows the obtained \( a \) and \( b \) values (columns 3 and 4). Runs 1-7 comply with the terms of the undistorted Earth magnetosphere. Runs 8-13 were carried out during a strong magnetosphere disturbance produced by the CME-driven interplanetary shock that reached the Earth at the end of the day 14.12.2006.
Table 1. Experimental and simulated values $a$ and $b$, obtained for the runs during solar events of 13-15 December, 2006.

| Number of run | Run time interval, UT | $a_{exp}$ ($\times 10^5$), 1/MV | $b_{exp}$ ($\times 10^2$), 1/MV | $a_{sim}$ ($\times 10^5$), 1/MV | $b_{sim}$ ($\times 10^2$) |
|--------------|-----------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------|
| 1            | 13.12.2006 03:08±03:13| 5.3±0.2                         | 3.0±0.2                         | 5.7±0.2                         | 2.7±0.1                   |
| 2            | 13.12.2006 03:59±04:04| 5.7±0.2                         | 3.2±0.2                         | 6.0±0.2                         | 2.4±0.1                   |
| 3            | 13.12.2006 04:19±04:24| 5.3±0.2                         | 3.2±0.2                         | 6.1±0.14                        | 2.0±0.2                   |
| 4            | 13.12.2006 08:36±08:42| 6.0±0.3                         | 2.3±0.3                         | 6.3±0.2                         | 1.7±0.1                   |
| 5            | 13.12.2006 09:00±09:05| 6.0±0.3                         | 2.9±0.2                         | 6.6±0.2                         | 1.3±0.1                   |
| 6            | 14.12.2006 09:44±09:50| 7.5±0.4                         | 1.4±0.4                         | 6.5±0.2                         | 1.8±0.2                   |
| 7            | 14.12.2006 10:05±10:11| 5.9±0.6                         | 3.4±0.5                         | 6.5±0.2                         | 1.6±0.1                   |
| 8            | 14.12.2006 22:57±23:03| 6.2±1.6                         | 4.5±1.4                         | 5.0±0.2                         | 8.5±0.2                   |
| 9            | 14.12.2006 23:26±23:31| 6.0±1.4                         | 5.6±1.3                         | 5.6±0.2                         | 6.8±0.2                   |
| 10           | 14.12.2006 23:49±23:54| 4.8±2.3                         | 8.9±2.3                         | 6.1±0.5                         | 6.8±0.6                   |
| 11           | 15.12.2006 00:18±00:23| 4.6±1.8                         | 6.7±1.6                         | 5.6±0.3                         | 6.3±0.5                   |
| 12           | 15.12.2006 01:22±01:28| -                               | -                               | 6.0±0.4                         | 6.3±0.6                   |
| 13           | 15.12.2006 01:54±01:59| 5.0±2.5                         | 7.1±2.1                         | 5.6±0.4                         | 5.5±0.6                   |

4. Investigation of $1/L_C^2(R)$ dependence during solar events with Monte-Carlo simulations

The linear $1/L_C^2(R)$ dependence was also verified by simulations. Efficiency dependences of SEP proton detection in the Earth’s magnetosphere on L-shell $Eff(L)$ during the solar events on 13.12.2006 – 15.12.2006 were simulated by means of Monte-Carlo method.

Implemented calculations were based on the assumption that SEP proton flux in studied point located inside magnetosphere is equivalent to the omnidirectional flux outside magnetosphere and is isotropic. The influence of the Earth magnetic field was reduced to the appearance of forbidden directions only. This assumption is founded on Liouville’s theorem. Therefore, evaluation of $Eff(L)$ was reduced to determine the fraction of particles from allowed directions in the telescope field of view.

The evaluation of $Eff(L)$ was carried out by the following algorithm. At the first step the isotropic flux of protons in PAMELA instrument field of view in the studied experimental energy interval (see previous paragraph) was modeled using the real proton spectrum measured with PAMELA during crossing the investigated polar cap (for example, see Fig. 3). As the result of this the statistics of occasional proton momentum vectors was collected. Then the penetration and physics interactions of the protons with modeled momentum vectors in PAMELA spectrometer frame were simulated with GEANT 4. The only events corresponding to trigger generating were taken into account. For each of six studied energy bins and each investigated polar cap the number of selected events $N_{sim}^{out}(\Delta E) = 200$ was collected.

At the second step the fraction of events with allowed trajectory in geomagnetic field $N_{sim}^{out}(\Delta E)$ was defined among simulated events $N_{sim}^{out}(\Delta E)$. This was implemented for each part of satellite orbit corresponding to the edge of investigated polar caps. To define the allowed events among the simulated ones the tracing of particle trajectories in geomagnetic field was carried out. Since the path of a positively charged particle of a specific magnetic rigidity is identical (except for the sign of the velocity vector) to that of a negatively charged particle reaching the same location in space, the common method of calculating cosmic ray trajectories in the Earth’s magnetic field is to calculate the trajectory in the reverse direction. Thus the starting point and initial direction for the reverse trajectory calculation were given by the PAMELA geographic coordinates and by the opposite direction of simulated particle momentum vector, correspondingly. The tracing of particle trajectories was fulfilled by the numerical integration of charged particle motion in geomagnetic field equation with fourth
order Runge-Kutta method. The geomagnetic field was modeled as superposition of internal (defined by IGRF model) and external (defined by Tsyganenko96 model) sources. The presence of Earth’s solid body and its atmosphere was taken into account. The real values of solar wind pressure, \( D_{st} \) index and the interplanetary magnetic field components \( B_y, B_z \) for the investigated period (see Fig. 2) were used as input parameters for the Tsyganenko96 model. For each investigated point in the satellite orbit and the energy bin \( \Delta E \) we have simulated \( N_{out}^{sim}(\Delta E) = 200 \) particle trajectories. A calculated trajectory was considered as forbidden if particle was lost in Earth’s atmosphere or could not escape magnetosphere for the fixed maximum path length, otherwise the event was considered to be allowed. Finally the simulated efficiency of SEP proton detection in the Earth’s magnetosphere by PAMELA instrument was obtained as: 

\[
    \text{Eff}(\Delta E) = \frac{N_{in}^{sim}(\Delta E)}{N_{out}^{sim}(\Delta E)}.
\]

Fig. 6 shows the simulated dependence \( \text{Eff}(L) \) for a period corresponding to one of the experimental runs. It is seen from Fig. 4 and Fig. 6, that experimental and simulation curves have a similar shape.

In the Fig. 5 the simulated \( \frac{1}{L_c^2}(R) \) dependence is presented together with experimental one, obtained for the same run 03:08–03:15 UT 13.12.2006. As it can be seen from the graph, the simulated dependence is also linear and practically coincides with the experimental one. Table 1 (columns 5 and 6) summarizes the \( a \) and \( b \) coefficients obtained from simulations.

### 5. Analysis of obtained results

Experimental and simulation \( \frac{1}{L_c^2}(R) \) dependences obtained for the undistorted conditions, and under conditions of strongly disturbed Earth magnetosphere, are close to be linear in the studied range of rigidities 640–2780 MV. The linearity of these curves gives the possibility to use the geomagnetic separator method for charge measurement of heavy ions with energies up to several hundreds of MeV/n.

Fig. 7 presents the dependence of experimental and calculated \( a \) (left) and \( b \) (right) coefficient values on time during the solar events of December 13–15, 2006. Grey color on the graph marks Earth magnetosphere strong distortion period (\( D_{st} < -60 \) nT). These dependences show that magnetosphere distortion has moderate influence on the coefficient \( a \) value (i.e., slope), and at the same time has a significant impact on the coefficient \( b \) value (i.e., the initial intercept).

As it can be seen from the Fig. 7 plots, the slopes \( a \) of experimental and calculated \( \frac{1}{L_c^2}(R) \) dependences are in agreement. The coefficients \( b \) are also in agreement, but are not so good. Thus obtained in the simulation \( \frac{1}{L_c^2}(R) \) dependences can be used for practice in realization of geomagnetic separator method. To precise (calibrate) the initial intercept of evaluated dependences \( b \) in real experiment the proton counting rate for at least the only one low-energy bin can be used. In MONICA experiment for this calibration the counting rate of protons will be measured with simple
proton monitor [1] in three energy (rigidity) bins: 20-30 MeV (195-239 MV), 80-90 MeV (396-421 MV), 110-120 MeV (467-489 MV). Particularly this correction is needed during the measurements under conditions of strongly disturbed Earth magnetosphere. Some discrepancy between the experimental and simulated data can be associated with the use of the external Earth’s magnetic field model Tsyganenko-96 in simulations, which does not take into account the dynamic magnetosphere distortion parameter variations depending on changes in the external environment.

![Figure 7](image.png)

**Figure 7.** The experimental and simulated a (left) and b (right) coefficient values versus time obtained during SEP events 13-15 December 2006.

6. **Conclusion**

In this paper the in-depth analysis of ion detection features in the Earth magnetosphere was carried out. The behavior of the dependence of inverse square of geomagnetic cut-off L-shell \( L_C \) on the particle rigidity \( R \) during the powerful SEP events 13-15 December, 2006 was studied experimentally and by simulation for different magnetosphere disturbance degrees. It was shown that the \( 1/L_C^2(R) \) dependence is linear in the studied range of rigidities 640-2780 MV. This suggests the possibility of geomagnetic separator method using for charge measurement of heavy ions with energies from 10 MeV/n up to several hundreds of MeV/n.

Good agreement of the experimental and simulated \( 1/L_C^2(R) \) dependences suggests that dependences obtained by simulation using the latest Earth’s magnetic field models, can be used in MONICA experiment as well as in other future experiments for the measuring of the cosmic ray ion charge with the geomagnetic separator method.

This work was supported by the RFBR, grant 13-02-00477.

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