Analysis of trajectories of primary particles and muons detected at the Earth's surface with different polarity of the Sun

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Abstract. The flux of cosmic rays passing through the heliosphere changes its characteristics (energy and angular distribution) due to the influence of the interplanetary magnetic field. Because of this, the muon flux produced by primary cosmic rays in the Earth atmosphere also changes its characteristics. Muons registered at the surface of the Earth are generated mainly by primary protons and helium nuclei with energies from 10 GeV to TeV. The trajectories of these particles in the heliosphere are significantly influenced by the interplanetary magnetic field. The construction of backward trajectories of particles from the Earth surface (detector) into the heliosphere region allows us to estimate the relationship between the trajectories of muons and primary particles. The trajectories of muons and parent protons and helium nuclei of various energies for positive and negative polarity of the Sun in a quiet period and under the influence of disturbances in the interplanetary magnetic field are presented. It is shown that the change in the polarity of the Sun and the influence of disturbances in the interplanetary magnetic field lead to qualitative changes in the regions of the heliosphere through which primary particles pass.

1. Introduction

The trajectories of charged primary cosmic rays (PCR) in the heliosphere are determined by the state of the interplanetary magnetic field (IMF) and the polarity of the Sun. Perturbations in the solar wind emanating from the Sun modulate the IMF and affect the PCR flux. With the help of ground-based cosmic ray detectors (neutron and muon), the variations in the PCR flux are investigated. In order to study these variations, it is necessary to know through which areas of the heliosphere pass the PCR (mainly protons and helium nuclei) which generate atmospheric neutrons and muons. Unlike neutron detectors, muon detectors can fix the direction of the registered muons. Knowing the direction of the muon in the detector, it is possible to build backward trajectories to the generation zone and then the trajectory of the proton or helium nucleus through the Earth’s magnetosphere into the heliosphere. In this paper, the behavior of the primary protons trajectories in a quiet condition in the interplanetary magnetic field and under the influence of disturbances in the interplanetary magnetic field at negative and positive polarity of the Sun is discussed.
2. Atmosphere

Propagation of charged cosmic ray particles through the atmosphere of the Earth is accompanied by their interaction with nuclei of atoms of the atmosphere and energy losses. At interactions of primary particles, rapidly decaying pions and kaons are formed, they generate the atmospheric muon flux. The probability of interaction depends on the density of the atmosphere and the length of the way passed by particles. Energy losses - ionization and radiation - also depend on density of the atmosphere and the length of the way. The density of the atmosphere in its any point in geodetic coordinates WGS84 for the number of the day relative to the beginning of the year and the time of the day is given with empirical model of the atmosphere NRLMSISE-00 [1].

The altitude at which the interaction occurs (15 - 20 km) depends on the trajectory of the primary particle. At construction of the backward trajectory, this altitude can be estimated by means of numerical integration of the density along a direction of backward motion of a muon up to the atmosphere boundary, that is to calculate atmospheric depth (see figure 1). If the depth is less than a preset value (for example, 100 g cm\(^{-2}\)) muon is replaced with a parent particle (proton or helium nucleus).

![Figure 1. The altitude of the zone of muon generation is determined by atmospheric depth along the backward trajectory.](image)

Ionization loss for muon, proton and helion, and also radiation loss of muon are taken into account according to known formulas [2]. The step along the trajectory \(\Delta r\) for muon must be chosen small enough, for example, \(\Delta r = 10\) m or \(\Delta r = (20\) m)/\(\cos \theta_o\), but not more than 150 m.

3. Earth magnetosphere

The magnetic field of the Earth has a complicated spatial distribution. For its description, various models are used. In our case, the necessary model should allow to get an estimation of a vector of a magnetic field in all magnetosphere regions for the preset time. Such opportunity provide the models of the magnetic field of the Earth by N.A.Tsyganenko TS05 (distant field) and GEOPACK-2008 (near-field) [3].

For the beginning, it is necessary to prepare input parameters describing a solar wind and geomagnetic conditions for the preset time. For this purpose, it is possible to take advantage of the data [4] or to calculate them with the use of database OMNI [5] by the algorithm described there. After preparation of input parameters, initialization with the use of subroutine RECALC_08 is carried out.

As the trajectory of particles can pass through regions with a big gradient of the magnetic field (cusp, magnetic anomalies) it is necessary to use a step along trajectory \(\Delta r = 200\) m. At construction of the backward trajectory, it is necessary to check overrunning by the particle of the magnetosphere boundary. It is done with the help of subroutines GEOGSW_08 and SHUETAL_MGNP_08. After overrunning of the magnetosphere boundary, the particle appears in the interplanetary magnetic field.

4. Interplanetary magnetic field

Unlike the characteristics of the atmosphere and magnetosphere which can be approached in part to real, distribution of the magnetic field in the interplanetary space is not known. Only in the locations
of space vehicles which are equipped with the corresponding equipment it is possible to get a real vector of the magnetic field. In the given work, the model of the interplanetary magnetic field considered in [6] was used. The following equations and parameters were used to calculate the magnetic field beyond the Earth’s magnetosphere:

\[
B_{\varphi}(r, \theta, \varphi) = A \cdot S(\vec{r}) \cdot B_0 \left( \frac{r_0}{r} \right)^2,
\]
\[
B_{\theta}(r, \theta, \varphi) = 0;
\]
\[
B_\varphi(r, \theta, \varphi) = -A \cdot S(\vec{r}) \cdot B_0 \frac{\Omega}{V_{SW}} \left( r - b \right) \left( \frac{r_0}{r} \right)^2 \sin \theta,
\]
\[
\cos \theta_{HCS} = -\sin \alpha_{HCS} \cdot \sin \left( \varphi + \varphi_{HCS} + \frac{\Omega}{V_{SW}} r + \varphi_{0HCS} \right),
\]
\[
\Phi_{0HCS} = -\varphi_{Earth} + \frac{\Omega}{V_{SW}} r_{Earth},
\]
\[
S(\vec{r}) = \begin{cases} 1, & \text{if } \cos \theta > \cos \theta_{HCS}, \\ -1, & \text{if } \cos \theta \leq \cos \theta_{HCS}. \end{cases}
\]

where \( \vec{r}, r, \theta \) and \( \varphi \) are radius-vector and spherical coordinates in the HEEQ (Heliospheric Earth Equatorial) system [7]; \( B_\varphi, B_\theta, \) and \( B_0 \) are magnetic field projections; \( r_0 = 1 \) a.u.; \( b = 0.005 \) a.u.; \( B_0 = 5 \) nT is the magnetic field at distance \( r_0 \); \( \Omega = 2.865 \cdot 10^6 \) radian\( \cdot \)s\(^{-1} \) is the Sun’s equatorial angular velocity; \( V_{SW} = 400 \) km\( \cdot \)s\(^{-1} \) is the solar wind speed; \( A = \pm 1 \) is the Sun polarity and \( S(\vec{r}) = \pm 1 \). If the point with coordinates \( (r, \theta, \varphi) \) lies above the current sheet, \( S(\vec{r}) = +1 \); otherwise \( S(\vec{r}) = -1 \). Further, \( \varphi_{HCS} \) is the phase shift at the current sheet; \( \varphi_{0HCS} \) is the initial phase of the current sheet; \( r_{Earth} \) and \( \varphi_{Earth} \) give the Earth’s position; \( \theta_{HCS} \) is an operational variable; \( \alpha_{HCS} \) is the slope of the current sheet.

5. Motion in magnetic field
Motion of the relativistic charged particles in the magnetic field is described by the formula:

\[
m \frac{d}{dt} \gamma \vec{v} = q \left( \vec{v} \times \vec{B} \right), \quad \gamma = \frac{E}{E_0} + 1, \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}}.
\]

Here: \( m, q \) are mass and charge of the particle; \( \gamma \) is Lorentz factor; \( \vec{v} \) is unit vector of velocity; \( E, E_0 \) are kinetic and rest energies; \( \vec{B} \) is the vector of a magnetic field; \( t \) is the time.

Let us notice that movement in the magnetic field of particles of different types will be similar at equal values of \( q / (m \gamma) \). Therefore, the motion of proton (rest energy \( E_{0p} \)) with kinetic energy \( E_p \) will be similar to motion of \( ^4 \)He (\( \alpha \)-particle with rest energy \( E_{0\alpha} \)) with kinetic energy \( E_\alpha \):

\[
E_\alpha = 2E_p + 2E_{0p} - E_{0\alpha} \approx 2E_p - 1.85 \text{ [GeV]}.
\]

In [8], detailed description of the construction of the backward trajectory and examples of trajectories of protons with kinetic energy 20 GeV for positive muon with kinetic energy 3 GeV registered in a vertical direction at three points on the surface of the Earth (Apatity, Khabarovsk, Moscow) and examples [9] of the trajectories (in HEEQ) with a sloped current sheet (\( \alpha_{HCS} = 10^\circ \)) are given.
6. Behavior of primary protons at different polarities of the Sun and under the influence of the disturbance in the interplanetary magnetic field

Below, the behavior of the trajectories of primary protons with energy 20 GeV in a quiet condition in the interplanetary magnetic field and when the Earth is in a closed region of anomalous vertical component of the interplanetary magnetic field $B_z$ (the influence of the disturbance in the interplanetary magnetic field) on June 22 at 4 hours and 16 hours (when the asymptotic directions look towards and from the Sun, respectively) at negative ($A < 0$) and positive ($A > 0$) polarity of Sun are discussed. The region of anomalous $B_z$ is at distance $R \approx 0.85 - 0.9$ and $R \approx 1.05 - 1.1$ a.u. from the Sun. At the chosen date, inclination and displacement of the current sheet, the Earth is located above the heliospheric current sheet.

Figure 2 shows trajectories of primary protons in quiet condition of the interplanetary magnetic field on June 22 at 4 hours at negative ($A < 0$) (figure 2, a) and positive ($A > 0$) (figure 2, b) polarity of the Sun.

Figure 3 shows that on June 22 at 4 hours the region of anomalous $B_z$ (the circle in the figure) is at distance $R \approx 0.85 - 0.9$ a.u. from the Sun and reflects the trajectory of primary protons for events:

a) $A < 0$, $B_z = -30$ nT; b) $A > 0$, $B_z = -30$ nT; c) $A < 0$, $B_z = +30$ nT; d) $A > 0$, $B_z = +30$ nT.

Figure 2. Trajectories of primary protons in quiet condition of the interplanetary magnetic field at negative (a) and positive (b) polarity of the Sun.

Figure 3. Trajectories of primary protons in the region of anomalous of $B_z$ on June 22 at 4 hours at negative ($A < 0$) and positive ($A > 0$) polarity of the Sun at distance $R \approx 0.85 - 0.9$ a.u. from the Sun.
If the Earth is inside the closed region of anomalous $B_z$ ($R \approx 1.05 - 1.1$ a.u.), this region limits access of primary protons from outside. Partially trajectories of primary protons come outside of the region of the anomalous $B_z$ (at negative polarity) or completely do not come from outside (at positive polarity). The influence of the anomalous $B_z$ region is stronger for events $A > 0$, $B_z = -30$ nT and $A < 0$, $B_z = +30$ nT, and weaker for other examples in figure 4 on June 22 at 4 hours and 16 hours:

a, c) $A > 0$, $B_z = -30$ nT; b, f) $A > 0$, $B_z = -30$ nT; c, g) $A < 0$, $B_z = +30$ nT; d, h) $A > 0$, $B_z = +30$ nT.

**Figure 4.** Trajectories of primary protons in the region of anomalous $B_z$ on June 22 at 4 hours and 16 hours at negative ($A < 0$) and positive ($A > 0$) polarity of Sun at distance $R \approx 1.05 - 1.1$ a.u. from the Sun.
7. Conclusion
The described method of construction of backward-trajectories at different polarities of the Sun allows to study the behavior of trajectories of primary protons which give contribution to the muon flux registered at the Earth surface by the muon hodoscope URAGAN under the influence of disturbances in the interplanetary magnetic field. If the Earth is inside a closed region with an anomalous $B_z$, a decrease of the muon flux can be observed. The decrease of the muon flux depends on both the polarity of the Sun and the sign of $B_z$.

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