PRIMARY HELIUM CR INSIDE THE MAGNETOSPHERE: A TRANSMISSION FUNCTION STUDY

P. BOBIK\textsuperscript{1}, M.J. BOSCHINI\textsuperscript{2,∗}, M. GERVASI\textsuperscript{2,3}, D. GRANDI\textsuperscript{2}, K. KUDELA \textsuperscript{1} AND P. G. RANCOITA\textsuperscript{2}

\textsuperscript{1} Institute of Experimental Physics, Kosice, Slovak Republic
\textsuperscript{2} Instituto Nazionale di Fisica Nucleare, Milano, Italy
\textsuperscript{3} Physics Department - University of Milano Bicocca, Italy
E-mail: bobik@saske.sk

We have applied the Transmission Function approach to evaluate the primary Helium CR spectrum inside the magnetosphere. We have evaluated the trajectories of simulated alpha particles through the Earth magnetic field by backtracing up to the magnetopause or down the atmosphere. In this way we have computed first the transmission function for a particular position inside the magnetosphere; then we have evaluated the spectrum of primaries, propagating a energy population of GCR. The analysis has been restricted to the geographic coverage of the AMS-01 detector (between 51.6 and -51.6 degrees) and altitude (400 km) and divided in geomagnetic zones. Finally we have compared our results with the measured data.

1. Introduction

Isotropically distributed particles outside of Earth’s magnetosphere are inside magnetosphere affected by geomagnetic field. Calculation of particle trajectories in models of geomagnetic field [1],[2] are widely used for finding the distribution of these particles inside the magnetosphere. Transmission function [3] is a statistical approach based on trajectories calculations, used to evaluate particle intensity at selected points or regions in the magnetosphere. Cosmic ray spectrum at 1AU consist mainly of protons and Helium nuclei [4]. There were many measurements of CR Helium spectra inside the magnetosphere in the previous decades. Most precise were balloon measurements and AMS-01 spectrometer measurement during precursor flight of AMS project in june 1998. Precision of balloon experiments like BESS [5],[6], CAPRICE [7] and CREAM [8] is limited because of the effect

\textsuperscript{∗}CILEA, Segrate (Mi), Italy
2

of residual atmosphere, however, these are most precise measurements yet available except AMS-01 spectrometer measurements.

2. Method

2.1. Backtracing

Backtracing method [9],[10] is based on the inversion of charge sign (Zq) and velocity vector (v) in the equation of motion for a particle with relativistic mass m in the magnetic field B:

$$m \frac{dv}{dt} = Zq[v \times B]$$  (1)

Such inversion in equation (1) means that an antiparticle with rigidity R generated in a selected point and with initial direction has in magnetic field the same trajectory like a particle with same rigidity and direction coming to this point.

In all simulations presented in this article we used a combined model of geomagnetic field \( \vec{B} \). The total magnetic field \( \vec{B} \) consists of the external geomagnetic field described by the model Tsyganenko 96 [11] (see also the web site: http://nssdc.gsfc.nasa.gov/space/model/magnetos/data-based/modeling.html) and the internal geomagnetic field described by the IGRF model (see web site: http://nssdc.gsfc.nasa.gov/space/model/magnetos/igrf.html) : \( \vec{B} = \vec{B}_{\text{int}} + \vec{B}_{\text{ext}} \).

If the particle trajectory started from a selected location inside the magnetosphere crosses the magnetopause [12] at dayside of magnetosphere or a sphere with radius 25 Earth radii at nightside of magnetosphere we call it allowed trajectory. Trajectory crossing a sphere with altitude 40 km over the Earth or not crossing any of these borders after preselected number of calculations steps is forbidden trajectory.

Following the Liouville theorem, if the cosmic ray flux is isotropic outside the magnetosphere, the flux in a random point inside the magnetosphere is same in all the directions allowed for primaries, while it is zero in the forbidden directions [13]. Allowed trajectories are trajectories of primary cosmic rays (PCR) inside the magnetosphere. Forbidden trajectories can contain just secondary particles created in interactions with the atmosphere.

We provide such calculation for 3600 locations distributed uniformly over a complete sphere surrounding Earth at an altitude 400 km. Space Shuttle orbits ( \( |\theta_{\text{lat}}| \leq 51.6^\circ \) ) cover 78.9% of all calculated locations.
For every location we calculate particle trajectories in 270 isotropically distributed directions within the outward hemisphere inside the 32° acceptance cone (around the local geocentric Zenith) of the AMS-01 spectrometer. In every direction we determine 310 trajectories inside 31 rigidity intervals of the AMS-01 data (from 0.37GV to 200GV). To take into account the energy dependence of the proton flux, each energy interval has been subdivided in 10 equally spaced sub-intervals.

Table 1. Geomagnetic regions covered by AMS-01 measurements [14]. The regions are defined using the Corrected Geomagnetic latitude (CGM).

<table>
<thead>
<tr>
<th>Region ($M$)</th>
<th>CGM latitude $\theta_M$ (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0 \leq</td>
</tr>
<tr>
<td>2</td>
<td>$0.4 \leq</td>
</tr>
<tr>
<td>3</td>
<td>$0.8 \leq</td>
</tr>
</tbody>
</table>

### 2.2. Transmission Function

Transmission function ($TF$ hereafter) is a probability function of particle rigidity and position inside the magnetosphere. $TF$ shows the probability of a particles from the magnetopause with rigidity in range $\Re \pm d\Re$ to reach a selected point (or region) inside the magnetosphere. In our calculation $TF$ shows the probability of a particle with energy from selected AMS energy sub-bin to reach chosen geomagnetic region at low orbit. We determine $TF$ for 3 geomagnetic regions (see Table 1.), for which the AMS-01 data are available. South-Atlantic anomaly region was excluded (i.e. the region with latitude between $-55^\circ$ and $0^\circ$ and with longitude between $-80^\circ$ and $20^\circ$).

The value of transmission function for trajectory of particle with rigidity $\Re$ is equal 1 for allowed trajectory and equal 0 for forbidden trajectory. $TF_M(\Re_b, i_M)$ is the transmission function for location $i_M$ inside magnetosphere for particle with rigidity $\Re_b$ from $b^{th}$ rigidity bin. Value of $TF_M(\Re_b, i_M)$ is ratio of number of allowed trajectories to total number of trajectories at $i_M$ location in $b^{th}$ rigidity bin. In our article has $TF_M(\Re_b, i_M)$ value for trajectories with directions inside AMS-01 spectrometer acceptance cone.
Figure 1. $TF_M(\mathcal{R}_b)$ for all three geomagnetics regions.

For the location $i_M$, $TF_M(\mathcal{R}_b, i_M)$ is given by:

$$TF_M(\mathcal{R}_b, i_M) = \sum_{s=1}^{10} w_{b,s} \frac{N_{all}^{i_M}(\mathcal{R}_{b,s})}{N_{all}^{i_M}(\mathcal{R}_{b,s}) + N_{forb}^{i_M}(\mathcal{R}_{b,s})}$$

where $\mathcal{R}_{b,s}$ is the mean rigidity of the $s^{th}$ sub-interval of width $\Delta \mathcal{R}_b/10$ for the $b^{th}$ rigidity bin, $N_{all}^{i_M}$ is the number of allowed trajectories and the total (allowed and forbidden) number of computed trajectories is $N_{total}^{i_M} = N_{all}^{i_M} + N_{forb}^{i_M}$. The sub-intervals of rigidity bins have been weighted as function of their relative fluxes. For rigidities larger than 10 GV, the weights, $w_{b,s}$ (where $\sum_{s=1}^{10} w_{b,s} = 1$), are derived by the flux dependence on the proton rigidity $\mathcal{R}$, i.e $\phi(E) \propto \mathcal{R}^{-2.78}$ [14]. Below 10 GV, since the rigidity distribution becomes less steep, the sub-interval flux variation has been interpolated using three adjacent rigidity bins.

Transmission function for region $M$ is averaged from all $TF_M(\mathcal{R}_b, i_M)$ in region.

$$TF_M(\mathcal{R}_b) = \frac{\sum_{i_M} TF_M(\mathcal{R}_b, i_M)}{\sum_{i_M}}$$

where $\mathcal{R}_b$ is the particle rigidity in the $b^{th}$ rigidity interval of width $\Delta \mathcal{R}_b$.
and $\sum i_M$ is the total number of locations for the same region. $TF_M(\mathcal{R}_b)$ for all three geomagnetic regions are present at Figure 1.

![Figure 2. Comparison of evaluated primaries with AMS-01 He fluxes for 1st geomagnetic region.](image)

### 2.3. Flux at low orbit reconstruction

We take published differential primary AMS-01 helium spectra [15] as flux at 1AU outside the magnetosphere $\Phi_{1AU}(\mathcal{R}_b)$. For the AMS-01 observations, the predicted PCR fluxes per unit of solid angle [$\Phi_M(\mathcal{R}_b)$] in geomagnetic region ($M$) are obtained by convolving the transmission function of geomagnetic region ($M$) with the estimated AMS-01 flux $\Phi_{1AU}(\mathcal{R}_b)$ [14] at 1 AU, i.e. outside the magnetosphere, as functions of the helium rigidity ($\mathcal{R}_b$). Thus, we have

$$
\Phi_M(\mathcal{R}_b) = \Phi_{1AU}(\mathcal{R}_b) \cdot TF_M(\mathcal{R}_b).
$$

(4)

The SCR fluxes per unit of solid angle $\Phi_M^s(\mathcal{R}_b)$ can be obtained as

$$
\Phi_M^s(\mathcal{R}_b) = \Phi_{1AU}^{exp}(\mathcal{R}_b) - \Phi_M(\mathcal{R}_b).
$$

(5)
3. Computational Results

AMS collaboration published the He fluxes in all three geomagnetic regions [16]. These fluxes contain all registered He particles included also secondaries. In the figures 2., 3. and 4. we compare our evaluated primary fluxes in different geomagnetic regions with AMS published fluxes. As we can see at figure 2., computed PCR spectrum for first geomagnetic region, so for region with highest cut-off rigidity is very similar to the measured AMS-01 helium spectrum. This means that in penumbra part of helium spectra is ratio of SCR to PCR small in first geomagnetic region. Figure 3. shows comparison of evaluated PCR in second geomagnetic AMS-01 region with AMS-01 measured data. Evaluated PCR are lower than the measured helium data. The difference is due to relatively bigger ratio of SCR to PCR in the penumbra part of spectra in second region. Figure 4. show same comparison in the region with lowest cut-off.

4. Conclusions

A back-tracing procedure of simulated He nuclei entering the AMS-01 spectrometer has provided the fraction of allowed trajectories of primary cos-
mic rays (PCRs). Consequently, it has allowed to determine the so-called Transmission Function (TF) able to describe the transport properties of the PCRs to the space surrounding the Earth (at altitude of about 400km) from the upper limit of the geomagnetic field i.e. the magnetopause located at 1AU. The TF has finally allowed to determine the He fluxes of the PCRs in the 3 geomagnetic regions for comparison with the AMS-01 observations.

References