COSMIC RAY SPECTRUM AT 1 AU:
A TRANSMISSION FUNCTION APPROACH TO THE MAGNETOSPHERE


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ABSTRACT

We have used a method based on the transmission function to evaluate the effects of magnetosphere on the galactic cosmic rays at 1AU. The approach is based on calculation of trajectories (back-tracing) of particles in a model of geomagnetic field. Transmission function between AMS-01 orbit, at an altitude of 400 km, and the magnetopause has been built. In this paper we present spectra at 1AU based on AMS-01 data, taken in June 1998. The evaluation of the transmission function for 2005, using CREME96 model, is also presented. This method can be used to recover the spectrum outside the magnetosphere, starting from a measured spectrum of primaries in near Earth orbit, when the conditions of the data taking are known.

1. INTRODUCTION

Models of magnetosphere built in the past years [1] allow to obtain accurate transmission function for particles inside the magnetosphere. The concept and limits of the transmission function approach are described elsewhere [2]. Transmission function TF(ℜ) is a probability function, describing the possibility that a particle with rigidity ℜ reaches a point inside the magnetosphere: in our special case we are interested to the regions covered by AMS orbit. Usually the transmission function (TF hereafter) describes a probability for a range of rigidities from ℜ-∆ℜ to ℜ+∆ℜ. In the present paper we consider the probability for particles with energies inside the AMS experiment energy bins [3].

To evaluate the TF we use the calculation of trajectories in geomagnetic field for a set of points at the AMS orbit. Back-tracing calculation of the TF is based on the assumption that cosmic rays at 1AU are isotropically distributed in space. The Liouville theorem can be applied: if the cosmic ray flux is isotropic at 1AU outside the magnetosphere, the flux in a random point inside the magnetosphere is the same in all the directions allowed for primaries, while it is zero along all the forbidden directions [4].

The transmission function applies of course only to primary particles, i.e. particles coming from outside the magnetosphere. The cut-off rigidity is a transition region for the TF: primary particles with rigidity lower than cut-off can not penetrate the magnetosphere, while trajectories of very high energy particles are unaffected. Besides, trajectories forbidden to primaries are allowed (and possibly populated) to secondary particles, i.e. particles generated (or simply scattered) inside the magnetosphere (in particular in the highest shells of the atmosphere). Therefore the measured flux coming from these forbidden directions can be different from zero.

Back-tracing method is described in many articles [5]. This method is based on the charge sign and velocity vector inversion in the equation of motion for a particle in a magnetic field \( \mathbf{B} \):

\[
\frac{m \frac{d\vec{v}}{dt}}{Z q} = -\vec{v} \times \vec{B}
\]

where \( m \) is the relativistic mass of the particle, \( \vec{v} \) is the velocity, \( Z q \) is its charge and \( \vec{B} \) is the magnetic field. For our simulation we have used as external geomagnetic field the Tsyganenko96 model [1] (for a complete description of the code see the web page: http://www-istp.gsfc.nasa.gov/Modeling/T96.html) and as internal geomagnetic field the IGRF model (DGRF 2000 – 2005) [6] (for a full description see the web page: http://www.ngdc.noaa.gov/IAGA/wg8/table1.txt). Details of calculation are described elsewhere [7].

2. THE TRANSMISSION FUNCTION

We build transmission functions for different regions of AMS orbit [3]. As a result we have a set of 10 transmission functions, one for each AMS region (see table 1). Starting positions of back-tracing cover a complete sphere surrounding the Earth at AMS altitude (400 km). This grid of points has been built in order to have the same elementary shooting surface. For every position in the grid, starting directions are uniformly distributed in a 2\( \pi \) hemisphere. All AMS energy bins are covered in the simulation. In order to fit the AMS-01 experimental conditions we restricted the analysis as follows: geographical polar regions have been excluded.
(-51.6° ≤ latitude ≤ +51.6°); incoming directions are restricted to a cone of 32° from the detector axis; pointing direction is fixed at the zenith.

### TABLE 1 : AMS-01 geomagnetic regions.

<table>
<thead>
<tr>
<th>Region number</th>
<th>Geomagnetic latitude range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region 1</td>
<td>Θm &lt; 0.2</td>
</tr>
<tr>
<td>Region 2</td>
<td>0.2 ≤ Θm &lt; 0.3</td>
</tr>
<tr>
<td>Region 3</td>
<td>0.3 ≤ Θm &lt; 0.4</td>
</tr>
<tr>
<td>Region 4</td>
<td>0.4 ≤ Θm &lt; 0.5</td>
</tr>
<tr>
<td>Region 5</td>
<td>0.5 ≤ Θm &lt; 0.6</td>
</tr>
<tr>
<td>Region 6</td>
<td>0.6 ≤ Θm &lt; 0.7</td>
</tr>
<tr>
<td>Region 7</td>
<td>0.7 ≤ Θm &lt; 0.8</td>
</tr>
<tr>
<td>Region 8</td>
<td>0.8 ≤ Θm &lt; 0.9</td>
</tr>
<tr>
<td>Region 9</td>
<td>0.9 ≤ Θm &lt; 1.0</td>
</tr>
<tr>
<td>Region 10</td>
<td>1.0 ≤ Θm</td>
</tr>
</tbody>
</table>

For each point of the grid and for every rigidity Ρ we evaluated the ratio of the number of allowed trajectories over the number of all the directions, taking into account the described experimental geometry. This ratio is the probability for particles with rigidity Ρ to reach this point starting from outside the magnetosphere. This ratio is then averaged over every point for each AMS region and for each rigidity bin. This average ratio represents the transmission function for a particle with rigidity Ρ inside the actual AMS region. It is a wide region average of a very complex structure of penumbra changing from position to position inside the AMS region, and showing a very fine energy structure [2].

In figure 1 the TF evaluated for the ten different geomagnetic regions of AMS orbit is shown. Calculation has been performed taking into account the geomagnetic conditions present during the AMS-01 observations (June 1998). Geomagnetic regions are numbered starting from the geomagnetic equator (region 1) and going toward higher geomagnetic latitudes (region 10). Limits of the geomagnetic regions are indicated in table 1. As we can expect low energy particles have higher probabilities, i.e. can reach low orbit easily, moving towards the polar regions.

### 3. EVALUATION OF PRIMARIES’ SPECTRA

#### 3.1 Primaries in AMS region

AMS-01 has measured the spectrum of protons (both primaries plus secondaries) for the ten geomagnetic regions and obtained the full spectrum of cosmic (primary) protons in the energy range: 0.22 – 200 GeV [8]. We can construct primary proton spectra at near Earth orbit (altitude 400km) starting from the measured AMS-01 cosmic proton spectrum (SAMS) and the TF computed for the geomagnetic region $i$. We can write:

$$S_{Earth \ orbit}(i) = S_{AMS} \cdot TF(i)$$  \hfill (2)

Results are presented in figure 2. A comparison of these primary spectra with the complete measured spectra is shown in figure 3. Here we can see as the cut-off at low rigidity is sharper than corresponding measured spectrum. This can be explained with the presence of secondary protons with energy above the cut-off of primaries.

#### 3.2 Spectra outside the magnetosphere at 1AU

The reverse procedure can be also applied: if the primary proton spectrum in a certain geomagnetic region inside the magnetosphere is known the cosmic spectrum outside the magnetosphere can be recovered. Using primary cosmic rays at AMS orbit and TF in different regions we can build the differential spectrum of protons outside the magnetosphere at 1AU. In this
case we use the inverse relation

$$S_{1AU} = \frac{S_{AMS}(i)}{TF(i)}$$  \hspace{1cm} (3)

Where $S_{1AU}$ is the spectrum at 1AU outside the magnetosphere and $S_{AMS}$ is the primary AMS spectrum of the region $i$. An independent spectrum of primaries can be obtained from AMS-01 flux data through the separation by back-tracing of the measured particles. This analysis is still in progress [9].

Fig. 3. AMS-01 measured spectra (label AMS-01) compared with the evaluated primary spectra (label TF), for the geomagnetic regions 5, 7, and 10.

The same procedure could be also applied to every measured spectrum of primary CRs inside the magnetosphere. In fact the transmission function can be evaluated if the experimental conditions are known: time, position, and attitude of the experiment. Note that if we construct spectra at 1AU outside the magnetosphere using the transmission function we are restricted to energies higher than cut-off rigidity of the AMS regions. In fact below the cut-off rigidity the transmission function is equal to zero and the procedure fails. In this sense the region at higher geomagnetic latitude (region 10) gives us the widest information because its accessibility is extended to the lowest energies.

4. PREDICTION FOR THE FUTURE : AMS-02 ON THE INTERNATIONAL SPACE STATION

We can also use this method to estimate particles’ flux in future experiments. For example we can evaluate the AMS-02 primary spectrum at low orbit. In fact the models of the magnetosphere (IGRF/DGRF and Tsyganenko96) can be extrapolated for the next years. In Fig. 4 we present transmission function for the region 10 for the time periods of June 1998 (AMS-01 data taking) and October 2005 (the scheduled time of AMS-02 launch on ISS).

Besides the model CREME96 [10] (see the Web page: http://crsp3.nrl.navy.mil/creme96) can be used as a reference modulated proton spectrum at 1AU.

Fig. 4. Transmission function in region 10 of AMS experiment for June 1998 and October 2005 periods.

CREME96 is not taking into account some of the effects of CR propagation in the solar cavity. For this reason we need to compare estimated flux of CREME96 with the experimental data. We used for comparison the experimental spectra of AMS-01 [8] and BESS98 [11] for the period of summer 1998 and CAPRICE94 [12] for 1994. Spectra related to 1998 are shown in figure 5. In both periods the CREME96 model is higher than measurements by a factor 1.2. A better agreement with data is found when the CREME96 spectrum is normalized by this ratio. This correspond to a variation of 20%, which is consistent with the CREME96 model uncertainty (25%). The comparison in the two periods indicates also that such a normalization is not time dependent.

Fig. 5. Comparison of CREME96 proton spectrum at 1AU with AMS-01 data taken in June 1998 and BESS98 balloon experiment operated in July 1998.

Using the TF and CREME96 model, both evaluated for October 2005, and equation (2) we obtain expected AMS-02 primary spectrum for 2005 in the several
geomagnetic regions. A comparison of the primary proton spectra in near Earth orbit for the region 10 evaluated for October 2005 and for June 1998 is shown in Figure 6. Predicted intensity of primary protons during AMS-02 flight is significantly lower than intensity during AMS-01 flight for energies higher than 270 MeV. A combination of a higher magnetospheric transmissivity and a lower intensity of protons outside the magnetosphere in October 2005 than in June 1998 leads to a higher proton intensities in AMS-02 spectrum for particles with energy lower than 270 MeV.

![Fig. 6. Primary proton spectra at AMS orbit for June 1998 and October 2005. Normalized CREME96 proton spectra outside the magnetosphere for the same periods are also shown.](image)

**CONCLUSION**

The method of the magnetospheric transmission function in combination with measured (AMS-01) and simulated (CREME96) cosmic protons spectra has been successfully used to obtain the flux of primaries at several geomagnetic regions inside the magnetosphere. As AMS-01 has shown, measured spectra of protons in near Earth orbit are contaminated by a population of secondaries. This method can be used to separate the contribution of primary protons to the measured spectra. Prediction for future experiments are also possible because both geomagnetic model and modulated proton model can be extrapolated. Moreover this method can be used to recover cosmic ray spectra outside the magnetosphere, starting from measured primary spectra in near Earth orbit, when the experimental conditions are known to allow the evaluation of the magnetospheric transmission function.

**REFERENCES**


