Propagation of Cosmic rays in the Heliosphere and in the Earth magnetic field

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Searching for the sources of Galactic cosmic rays
Propagation of Cosmic rays in the Heliosphere

Parker transport equation

Propagation in the heliosphere is described by Parker (1965) equation:

\[
\frac{\partial U}{\partial t} = \nabla \cdot \left( K^S \cdot \nabla U - V_{sw} U - \langle v_D \rangle U \right) + \frac{1}{3} \left( \nabla \cdot V_{sw} \right) \frac{\partial}{\partial T} \left( \alpha T U \right)
\]

\( U \) is Cosmic Rays number density per unit interval of kinetic energy

- **Diffusion**
  - Small Scale magnetic Field irregularity

- **Convection**
  - Solar wind moving out from the Sun

- **Drift**
  - Large scale magnetic field structure

- **Energetic Loss**
  - Due to adiabatic expansion of the solar wind
Propagation of CR in the heliosphere is described by Parker (1965) equation:

\[ \frac{\partial U}{\partial t} = \nabla \cdot \left( K^S \cdot \nabla U - \mathbf{V}_{\text{sw}} U - \langle \mathbf{v}_D \rangle U \right) + \frac{1}{3} \left( \nabla \cdot \mathbf{V}_{\text{sw}} \right) \frac{\partial}{\partial T} (\alpha T U) \]

A Monte Carlo Approach - Ito's lemma, see e.g. Gardiner, 1985
The 2D Heliosphere Modulation Monte Carlo Code: HelMod

Stochastic Differential Equations (SDE)

\[ dr = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 K_{rr}) dt - \frac{\partial}{\partial \mu} \left( \frac{K_{r \mu} \sqrt{1 - \mu^2}}{r} \right) dt + (V_{\text{sw}} + v_{d_r}) dt + (2K_{rr})^{1/2} R_r \sqrt{dt} \]

\[ d\mu = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r K_{\mu r} \sqrt{1 - \mu^2} \right) dt + \frac{\partial}{\partial \mu} \left( K_{\mu \mu} \frac{1 - \mu^2}{r^2} \right) dt - \frac{1}{r} v_{d_\mu} \sqrt{1 - \mu^2} dt \]

\[ + \frac{-2K_{rr}}{r} \left( \frac{1 - \mu^2}{2K_{rr}} \right)^{1/2} R_r \sqrt{dt} + \frac{1}{r} \left( 1 - \mu^2 \right) \frac{K_{\mu \mu} K_{rr} - K_{rr}^2}{0.5K_{rr}} \right)^{1/2} \]

\[ dT = -\frac{\alpha_{\text{rel}} T}{3r^2} \frac{\partial V_{\text{sw}} r^2}{\partial r} dt \]

2-Dimensional set of SDEs

Details of HelMod modulation code, and how to compute the SDE, could be found in [Bobik et al. Ap.J. 2012, 745:132]
The interplanetary magnetic field

The Sun’s magnetic field is transported with the Solar wind into space, forming the so-called Heliospheric Magnetic Field (HMF)

Parker Field

\[ B = \begin{cases} \frac{A}{r^2} \left[ e_r + \frac{r}{r_b} \delta(\theta) e_\theta - \Gamma e_\phi \right] [1 - 2H(\theta - \theta')] & \text{Polar regions} \\ \frac{A}{r^2} \left[ e_r - \Gamma e_\phi \right] [1 - 2H(\theta - \theta')] & \text{elsewhere} \end{cases} \]

Jokipii & Kota, 1989

Langner, 2004

The Polar Correction \( B_L \) is evaluated only

For \( \theta < 30^\circ \) and \( \theta > 150^\circ \) of solar colatitude

\[ B_P = \frac{A}{r^2} \left[ e_r - \left( \frac{(r-r_0)\omega \sin \theta}{V_{sw}} \right) e_\phi \right] [1 - 2H(\theta - \theta')] \]

\[ B_L = \frac{A \delta_m}{r_0 r \sin \theta} e_\theta \]

Diffusion

In the magnetic field line reference the diffusion tensor is

\[
K_{ik} = \begin{bmatrix}
K_{\perp r} & -K_A & 0 \\
K_A & K_{\perp \theta} & 0 \\
0 & 0 & K_{\parallel}
\end{bmatrix}
\]

\[
K_{\parallel} = \frac{\beta}{3} K_0 \frac{P}{1\text{GV}} \left(1 + \frac{r}{1\text{AU}}\right)
\]

[Strauss et al, 2011]

\[
K_{\perp \theta} = K_{\perp r} = \rho_k K_{\parallel},
\]

\(K_0(t)\) is the modulation parameter obtained using cosmic ray flux >2 GV measured with neutron monitor at different latitudes

- We apply modulation inside an effective spherical volume of 100 AU
- \(K_0(t)\) takes into account the rough **integrated effects** on GCR modulation as seen at the Earth position
- \(K_0(t)\) is sensitive to GCR particles with **rigidity > 2 GV** where different **LIS do not differ** practically each other
- Changing Heliosphere dimensions (80 – 120 AU) modulated spectra do not differ significantly, for **rigidity > 1 GV (> 400 MeV)**
We divide the Heliosphere in 15 regions, each one equivalent to the average of solar activity in periods before the experiment.

Parameters in each region are:

- Diffusion parameter
- Tilt angle of the Neutral Sheet
- Magnetic Field Magnitude at Earth
- Solar Wind Speed
Protons LIS

1. Model(s) independent from the LIS

2. Transmission function approach

3. Possibility use/test different LIS

Comparison between the Proton LIS from GALPROP (dash line, Trotta et al., 2011) and BPH-LIS (Solid line, Burger et al., 2000). The short-dot line correspond to 1 GV.
error-weighted root mean square of the relative difference between experimental data and those resulting from simulated differential intensities

$$\eta_{\text{rms}} = \sqrt[2]{\frac{\sum (\eta_i / \sigma_{\eta,i})^2}{\sum 1 / \sigma_{\eta,i}^2}}$$

$$\eta_i = \frac{f_{\text{sim}}(T_i) - f_{\text{exp}}(T_i)}{f_{\text{exp}}(T_i)}$$

**Table 2 and 4**

<table>
<thead>
<tr>
<th>Observations</th>
<th>“L” Model</th>
<th>“R” Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS–1999</td>
<td>8.7</td>
<td>8.0</td>
</tr>
<tr>
<td>BESS–2000</td>
<td>16.2</td>
<td>15.8</td>
</tr>
<tr>
<td>BESS–2002</td>
<td>12.7</td>
<td>15.0</td>
</tr>
<tr>
<td>BESS–1997</td>
<td>9.2</td>
<td>17.7</td>
</tr>
<tr>
<td>AMS–1998</td>
<td>4.6</td>
<td>7.9</td>
</tr>
<tr>
<td>BESS–1998</td>
<td>9.1</td>
<td>14.1</td>
</tr>
<tr>
<td>PAMELA–2006/08</td>
<td>7.1</td>
<td>13.4</td>
</tr>
</tbody>
</table>

**Table 2 and 4**

**Systematic Investigation of Solar Modulation of Galactic Protons for Solar Cycle 23 using a Monte Carlo Approach with Particle Drift Effects and Latitudinal Dependence**

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**ABSTRACT**

A propagation model of galactic cosmic protons through the Heliosphere was implemented using a 2-D Monte Carlo approach to determine the differential intensities of protons during the solar cycle 23. The model includes the effects due to the variation of solar activity during the propagation of cosmic rays from the boundary of the heliosphere down to Earth’s position. Drift effects are also accounted for. The simulated spectra were found in agreement with those obtained with experimental observations carried out by BESS, AMS and PAMELA collaborations. In addition, the modulated spectrum determined with the present code for the year 1995 exhibits the latitudinal gradient and equatorial southward offset minimum found by Ulysses fast scan in 1995.

*Subject headings:* Solar modulation, Interplanetary space, Cosmic rays propagation

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Figure 8. Differential intensity determined with the HelMod code (continuous line) compared to the experimental data of AMS–1998; the dashed line is the LIS (see the text).

Figure 10. Differential intensity determined with the HelMod code (continuous line) compared to the experimental data of PAMELA–2006/08; the dashed line is the LIS (see the text).

HelMod – selected results

antiproton over proton ratio at 1AU


Fig. 2. Comparison of simulated $\bar{p}/p$ ratio at 1 AU and experimental data: BESS (1997).

Fig. 3. Comparison of simulated $\bar{p}/p$ ratio at 1 AU and experimental data: PAMELA (2007–2008).

HelMod – selected results

**Fig. 2.** The cosmic ray positron fraction evaluated for a period corresponding to a typical solar minimum with both magnetic field polarities.

**Fig. 3.** Simulated electron spectrum for AMS-01 mission (1998).

**Fig. 4.** Simulated positron spectrum for AMS-01 mission (1998).

**Fig. 5.** Simulated cosmic ray positron fraction for AMS-01 (1998) and PAMELA (2006–2008).

S. Della Torre et al., Effects of solar modulation on the cosmic ray positron fraction, Advances in Space Research 49, 1587–1592, 2012
HelMod – selected results spectras at planet orbits

Evaluated primary proton flux at Earth (1AU) for positive solar period.

Proton flux at different distances (planets) in the solar system.
Latitudinal CR intensity dependence

From ‘90s up to 2010 ESA/NASA Ulysses mission explore the heliosphere outside the ecliptic plane

K.E.T. Instruments measured cosmic protons and electrons in energy range greater than 0.2 GeV.

The fast scan in 1995 (A>0) showed the presence of a latitudinal gradient of proton in the inner heliosphere. This gradient vanish during the 2007 (A<0) fast scan. Electrons show opposite behavior. [see e.g. Heber et al. Ap.J. 2008, 689:1443 and reference therin]
Drift effect on latitudinal gradient

We use HelMod Code with present model of $K_\parallel$ to evaluate the latitudinal gradient in both magnetic field polarity.

The presence (or not) of a latitudinal gradient is related to Drift mechanism in the heliosphere.

Since drift is related to the product of charge ($q$) and field Polarity ($A$), with electron opposite behaviors appears, in qualitatively agreement with Ulysses analysis.
Data comparison

To compare our results with Ulysses data, we evaluate the Cosmic rays intensity during the both two fast scan at the same distance and latitude of Ulysses Spacecraft (IU).

To take into account the time variation of the Cosmic rays intensity, we evaluate also the intensity at the same time at 1AU on ecliptica (IE) and renormalized the ratio IU/IE in order to have 1 at south pole (-90° ~ -70°).

The same is done both for Proton and Electron.
Results

A>0 Ulysses Fast Scan

S. Della Torre et al., A Monte Carlo study for 2-D Heliospheric modulation effects, ECRS, Moscow, 2012
HelMod - www.helmod.org

- Web version of model (ver. HelMod 1.5.)
- Model description + bibliography
- Spectra at 1AU catalogue

Web still in development

Jan 2013 – web release date
The Geomagnetic Field

The Earth magnetic field can roughly be considered as a dipole, whose axis is tilted with respect to the rotation axis and whose center is shifted with respect to the Earth’s center.

Due to the compression of the solar wind it becomes widely asymmetric with a long tail opposite to the Sun.
Propagation of Cosmic rays in the Earth magnetic field

**Internal geomagnetic field**

- The Internal Field
  - The Internal Geomagnetic Reference Field (IGRF) is the empirical representation of the Earth's magnetic field. IGRF represents the main (core) field without external sources.
  - Model is built by using a set of spherical harmonic coefficients (called Gauss coefficients) in a truncated series expansion of the internal geomagnetic potential

\[
V = R_e \sum_{n=1}^{N} \left[ \frac{R_e}{r} \right]^{n+1} \times \sum_{m=1}^{n} \left[ g_n^m \cos(m \phi) + h_n^m \sin(m \phi) \right] P_n^m(\cos \theta)
\]

- The IGRF model coefficients are based on all the available data sources including geomagnetic measurements from observatories, ships, aircrafts and satellites
- The IGRF model consist of a set of coefficients for the epoch starting from 1900 to 2010, in step of 5 years. During the 5-year intervals a linear interpolation is recommended.
Propagation of Cosmic rays in the Earth magnetic field

*Internal geomagnetic field*

**HORIZONTAL INTENSITY (NT)**

[Graph showing the horizontal intensity across various geographic coordinates]
Propagation of Cosmic rays in the Earth magnetic field

Internal geomagnetic field

VERTICAL COMPONENT: Z (nT)
Propagation of Cosmic rays in the Earth magnetic field

Internal geomagnetic field

TOTAL INTENSITY (NT)
External Field

Tsyganenko model:
• Data base approach from over 3 decades of measurements...
• All external currents contributions to external magnetic field
• 1996 model (solar wind controlled magnetopause Sibeck)
• 2001 and 2005 models (for SEP and CME events)

Tsyganenko 96

Depends on 4 main parameters: Dst, Pdyn By and Bz of IMF) Contains these main Magnetic field contribution:

• Magnetopause
• Ring Current (trapped)
• Tail current
• Bierkeland region 1
• Bierkeland region 2
• Interconnection field

All fields are empirically obtained by the 4 main parameters

Tsyganenko 05

New data from 1996 to 2000 (37 major events)
All components from 3 main parameters:
1. N density of SW
2. V speed of SW
3. B southward IMF components


Time scale of Tsyganenko 2001 is 1 hour, (symmetric rise and decay of solar event) while with Tsyganenko 2005 becomes asymmetric.

Plus in addition there is a Fast and Slower response of each Magnetic field component to the Storm
Tsyganenko parameters

96 model
1. Pdyn,
2. By, Bz
3. Dst

from OMNIWEB http://omniweb.gsfc.nasa.gov/

05 model
1. In addition new parameters (called W1, W2, W3, W4, W5, W6)
From OMNIWEB parameters recalculated “ad hoc”
$p_{\text{dyn}}$ evolution in last decades
p\textsubscript{dyn} evolution

\textbf{Description}

date :: 2004.6724
\[ p_{\text{dyn}} = 0.56000000 \text{ nT} \]

\textbf{Shape of magnetopause}


Year : Month : Day : Hour
2004 : 5 : 2 : 2
Description

date :: 2004.6753

\( p_{\text{dyn}} = 2.0100000 \ \text{nT} \)

Shape of magnetopause


Year : Month : Day : Hour
2004 : 8 : 3 : 4
Description

date :: 2004.6869

\( p_{\text{dyn}} = 8.1700000 \text{ nT} \)

Shape of magnetopause


Year : Month : Day : Hour

2004 : 8 : 7 : 9
Dst index evolution in last decades
$B_y$ Interplanetary magnetic field component at 1 AU
$B_z$ Interplanetary magnetic field component at 1 AU
Propagation of Cosmic rays in the Earth magnetic field

**Back-tracing method**

- **Method of calculation trajectory**
  - Usual approach to the trajectory calculations of cosmic rays in the geomagnetic field is based on the reversal of both the sign of the electric charge and the velocity of the particle in Lorentz equation.

\[
m \frac{d \vec{v}}{dt} = Zq (\vec{v} \times \vec{B})
\]

- Model of combined external (Tsyganenko 96, 2001 and Tsyganenko 2004) and internal geomagnetic fields (IGRF and DGRF)

\[
\vec{B} = \vec{B}_i + \vec{B}_e
\]

- We solve the Lorentz equation and propagates a particle backward in time

- Samples of **allowed** trajectories (projection to equatorial plane) for stations Lomnický Štít for 21. March 1986, 1.00 UT for particles with \( R = 4.0, 4.1, 4.2, 4.3, 4.4, 4.5, 5.0 \) and 20.0GV
A trajectory is assumed as **forbidden** if the particle, after a selected number of steps (25000) is neither crossing the magnetopause nor the sphere with a radius equal to 25 Re (on the night side). Moreover, a trajectory is assigned as a forbidden one also when it resulted crossing the Earth’s surface.

- Samples of forbidden trajectories (crossing the Earth) for Lomnický Štít station for 21.march 1986 1.00 UT, for particle with rigidity $\mathcal{R} = 3.25$GV
  - Length of trajectory = 210 050,4km
  - Time = 0.729 sec.

- Samples of forbidden trajectories (stoped after 250.000 steps) for Lomnický Štít station for 21.march 1986 1.00 UT, for particle with rigidity $\mathcal{R} = 2.25$GV
  - Length of trajectory = 3482824km
  - Time = 12.58864 sec.
Cut – off rigidity concept

- Penumbra structure is usually described as a system of allowed and forbidden trajectories (AF) between low, $\mathcal{R}_L$, and upper $\mathcal{R}_U$, cutoff rigidities.
- Example of spectrum allowed and forbidden (A,F) trajectories for Lomnický Štít 21. March 1986 1.00 UT. Rigidity step in calculation is 0.001 GV. Allowed rigidities are signed in black color, forbidden in white color.
Analysis of the AMS-01 experiment data taken during the STS-91 Space Shuttle mission in June 1998

Calculation has been performed taking into account the geomagnetic conditions present during the AMS-01 observations (June 2 – 12, 1998) : solar activity parameters have been averaged over the 10 days of the AMS-01 flight, while the chosen simulation time is June 8 (1998) at 10:00 am (UT).

Starting positions of back-tracing cover a complete sphere at an altitude of 400 km (following the AMS orbit). 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 $2\pi$ outgoing hemisphere.

Geomagnetic regions covered by AMS-01 measurements. The regions are defined using the Corrected Geomagnetic latitude (CGM).

Geomagnetic regions covered by AMS-01 measurements. The regions are defined using the Corrected Geomagnetic latitude (CGM).

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

The locations (3600) of the particles to be back-tracked are distributed over a complete sphere surrounding the Earth at an altitude of 400km and 78.9% of them are within the geographic latitudes of the orbits of the Space Shuttle, i.e. $|\theta_{\text{lat}}| < 51.6^\circ$, excluding the South-Atlantic anomaly region (i.e. the region with latitude between -55° and 0° and with longitude between -80° and 20°).

3600 locations

Propagating of Cosmic rays in the Earth magnetic field

Results examples - AMS-01

- For each point of the grid and for every rigidity $\Re$ we evaluated the ratio of the number of allowed trajectories over the number of all the directions.
- This ratio is the probability for particles with rigidity $\Re$ 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 and becomes the transmission function for a particle with rigidity $\Re$ inside the actual AMS region.
- At all was simulated $\sim10^9$ trajectories

The transmission function $TF(\Re)$ of the magnetosphere describes the probability that a particle with rigidity $\Re$, coming from outside, reaches a point inside the magnetosphere.

Bobik P. et al, Magnetospheric transmission function approach to disentangle primary from secondary cosmic ray fluxes in the penumbra region, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, A05205, 2006
Figure 4. Normalized fluxes per units of solid angle $\Phi_{M,N}^{\exp}(R_b)$ (see text for explanation of the symbol) are shown for the geomagnetic regions $M = 1, 4, 7, \text{ and } 10$ as functions of the proton kinetic energies.
Fluxes per units of solid angle as a function of the proton kinetic energy - AMS-01

1st geomagnetic region: (open circle) \( \Phi^{1\text{AU}}(R_b) \),
(solid circle) \( \Phi_1(R_b) \), and (square) \( \Phi_1^*(R_b) \)

seventh geomagnetic region: (open circle) \( \Phi^{1\text{AU}}(R_b) \),
(solid circle) \( \Phi_7(R_b) \), and (square) \( \Phi_7^*(R_b) \)

fourth geomagnetic region: (open circle) \( \Phi^{1\text{AU}}(R_b) \),
(solid circle) \( \Phi_4(R_b) \), and (square) \( \Phi_4^*(R_b) \)

tenth geomagnetic region: (circle) \( \Phi^{1\text{AU}}(R_b) \),
(solid) \( \Phi_{10}(R_b) \), and (square) \( \Phi_{10}^*(R_b) \)

Bobik P. et al, Magnetospheric transmission function approach to disentangle primary from secondary cosmic ray fluxes in the penumbra region, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, A05205, 2006
The particle directions are isotropically distributed within the outward hemisphere and inside the 45° acceptance cone (around the local geocentric Zenith) of the AMS-02 spectrometer. In addition, larger particle directions covering up to the full outward hemisphere have been back-tracked to investigate the TF dependence on the acceptance cone.

288 - directions

The TF has been computed for the rigidity intervals of the AMS-02 data, i.e. the lowest rigidity value is about 100 MV and the largest about 2 TV.

Bobik P. et al., The AMS-02 Proton Spectra and the Geomagnetic Field, Cosmic Rays for Particle and Astroparticle Physics, pp. 323-327, 2011
For the 10 geomagnetic regions, the $TF_M$ has been averaged over all uniformly distributed locations.

\[
TF_M(R_b) = \frac{\sum_{i_M} TF_M(R_b, i_M)}{\sum_{i_M}},
\]

where $R_b$ the particle rigidity in the $b$th rigidity interval of width $\Delta R_b$, $TF_M(R_b, i_M)$ is the transmission function for the position $i_M$ inside the geomagnetic region $M$ and $\sum_{i_M}$ is the total number of locations for the same region.

\[
TF_M(R_b, i_M) = \sum_{s=1}^{10} w_{b,s} \frac{N_{all}^{i_M}(R_b, s)}{N_{all}^{i_M}(R_b, s) + N_{forb}^{i_M}(R_b, s)},
\]

where $R_{b,s}$ is the mean rigidity of the $s$th sub-interval 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

\[
N_{total}^{i_M} = N_{all}^{i_M} + N_{forb}^{i_M}.
\]

Bobik P. et al., The AMS-02 Proton Spectra and the Geomagnetic Field, Cosmic Rays for Particle and Astroparticle Physics , pp. 323-327, 2011
Propagation of Cosmic rays in the Earth magnetic field

Results examples - AMS02

- HelMod

Modulated spectrum of CR at 1AU outside the magnetosphere for January 2012 (expected same condition as October 1987)

For details see HelMod model presentation S. Della Torre, *Electron and Positron solar modulation and prediction for AMS-02, ICATTP 2011*

Bobik P. et al., The AMS-02 Proton Spectra and the Geomagnetic Field, *Cosmic Rays for Particle and Astroparticle Physics*, pp. 323-327, 2011
Transmission function $TF_M$ for all geomagnetic regions $M$ for full outward hemisphere i.e. for geocentric zenith angle $90^\circ$.
Transmission function $TF_M$ for all geomagnetic regions $M$ for particle directions isotropically distributed within the outward hemisphere and inside the 45° acceptance cone (around the local geocentric Zenith) of the AMS-02 spectrometer.

Primary proton spectra at the ISS orbit ($S_{ISS}$) can be evaluated by combining the HelMod cosmic proton spectrum ($S_{1AU}$) with the TF computed for the $M^{th}$ region:

$$S_{ISS} = S_{1AU} \times TF_M$$

Bobik P. et al., The AMS-02 Proton Spectra and the Geomagnetic Field, Cosmic Rays for Particle and Astroparticle Physics, pp. 323-327, 2011
Fluxes per units of solid angle are shown as functions of the proton kinetic energy.

Spectra evaluated for full outward hemisphere i.e. for geocentric zenith angle 90°
Fluxes per units of solid angle are shown as functions of the proton kinetic energy.

Fluxes for all geomagnetic regions $M$ for particle directions isotropically distributed within the outward hemisphere and inside the 45$^\circ$ acceptance cone (around the local geocentric Zenith) of the AMS-02 spectrometer.
Fluxes for detector acceptance cones of 45° and 90° (full sphere) around the local geocentric Zenith for geomagnetic regions $M = 1, 4, 7, 10$. 

Bobik P. et al., The AMS-02 Proton Spectra and the Geomagnetic Field, Cosmic Rays for Particle and Astroparticle Physics, pp. 323-327, 2011
Trajectory computations cover the period from 0 to 2000 A.D.

We use Gauss coefficients

g01, g11, h11, g02, g12, h12, g22, h22, g33, h33

collected from paper (Hongre et al., 1998, hereafter called n=2+) for years from 0 to 1700 A.D.

and

the same set of IGRF model's Gauss coefficients for years from 1900 to 2000.

Period between 1700 to 1900 is covered by calculations using g10, g11, h11 coefficients only (Bloxham and Jackson, 1992).
Long term variations of geomagnetic rigidity cutoffs
Long term variations of geomagnetic rigidity cutoffs

Long term changes of vertical cutoffs at selected longitudes.
Long term variations of geomagnetic rigidity cutoffs

The “global transmission function”: the fraction of the Earth’s surface at which the vertical access of cosmic rays for $R > R_c$ is allowed for different epochs.
• For now you can select
  • External field T96 or T05 (GeoMag-96 and GeoMag-05)
  • Epoch :: 1968-2012 for T96, 1995-2012 for T05
  • Altitude from Earth surface

Fixed:
• Internal field IGRF-11
• Compute vertical cutoff only
Thank you for your attention