Geomagnetic Backtracing: A comparison of Tsyganenko 1996 and 2005 External Field models with AMS-02 data

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Abstract: We used a backtracing code to reconstruct particle trajectory inside the Earth Magnetosphere during the last solar active period (2011 and 2012) when very high Solar Wind pressure values were measured. We compared our results on AMS-02 proton and electron data with 2 different External Field models, namely Tsyganenko 1996 (T96) and 2005 (T05), both for quiet (defined as the periods when the solar wind pressure is below the average value, set at 2nPa) and active periods. Although T05 has been specifically designed for storm events, at high energy the particle trajectory is similar for the two models. For instance at rigidities larger than 50 GV, the RMS of angular difference between reconstructed asymptotic direction outside the Magnetosphere is of the order of the millirad, while it increases at intermediate energies. We also confirmed, as a function of the pointing direction, the well known East-West effect on the trajectory of primary particles and on the access solid angle on the AMS detector.

Keywords: cosmic rays theory model and simulations, geomagnetic field

1 Introduction

To study the effect of the Earth magnetosphere on cosmic rays detected by the AMS experiment during its mission on board of the ISS (since May 2011) we developed a software code for particle tracing. Particles trajectories have been evaluated in the framework of the internal magnetic field IGRF-11 [1] and the external magnetic field Tsyganenko 96 and 2005 [2][3]. Several effects of the Earth magnetic field on charged particles outside the atmosphere have been studied. Our attention was focused on the two external field models, the first, Tsyganenko 96 (hereafter T96) that was developed for quiet geomagnetic periods, and the second, Tsyganenko 2005 (hereafter T05) that was developed with new data from 1996 to 2000, especially for storm events. For this study we were able to use values of the solar parameters measured during 2011 and 2012. Parameters for T96 were obtained from OMNIWEB [4] while parameters for T05 from the web repository [5] or directly provided by N. Tsyganenko itself. The backtracing provides the separation of allowed and forbidden primary particle trajectories and can be used to distinguish between primary and secondary CR. Among the Galactic Cosmic Rays (GCR), protons are largely the most abundant, but also the amount of Helium nuclei and electrons is relevant. In this work we selected only AMS-02 electrons and, in order to evaluate the effect of the external field, our analysis was restricted to primary (allowed) particles. Our results can be used for the study on electron and positron anisotropy, in order to take in proper account the effect of the Earth magnetic field, even at energies around 100 GeV. The presence of antimatter in cosmic rays (mostly positrons), has been observed by the AMS-02 experiment [6]. The fraction of positrons resulted to be increasing with energy, up to 350 GeV, putting the origin of this signal. Local astrophysical sources (within 1 kpc) like pulsars are not yet confirmed as possible explanation (see [7]). Further information can be obtained looking for the anisotropy in the spatial distribution of these particles.

2 Particle Tracing in the Geomagnetic Field

The Earth magnetic field can be roughly seen as a magnetic dipole, whose axis is shifted from the Earth center of ~500 km, inclined of ~11° and opposite to the geographic rotational axis. Because of the presence of the solar wind, the magnetic field is hardly compressed in the dayside and smoothly decompressed in the nightside, creating a highly asymmetric magnetosphere configuration. Inside this region, due to the Lorentz force, positive charged particles coming from outside the magnetosphere are rotated clockwise and negative charged particles counterclockwise. To describe the effect of magnetic fields on charged particles we can use the magnetic rigidity $R$, essentially the ratio between the momentum of the particle and its charge ($Ze$). Particle trajectory in the “almost dipolar” Earth magnetic field is more curved the lower is its momentum (energy), so from previous formula we can define for every point in space a limit called rigidity cut-off [8], below which primary cosmic rays will never reach any detector in orbit around the Earth.

$$R_{\text{cut}} \geq 59.6 \cdot \left[ 1 - \sqrt{1 - \cos \Theta_{an} \cdot \cos \gamma} \right]$$

(1)
Where $R_{cut}$ is in GV, $\theta_{cut}$ is the magnetic latitude (see par.4) and $\gamma$ is the angle between particle velocity and East-West geomagnetic direction (from East to West).

We need to reconstruct the particle trajectory to study the properties of cosmic rays detected by AMS, especially across the rigidity cut-off. Eq.1 can still be useful only in relation with an empirical estimate of the confidence level of this sharp edge. We define $R_{cut}$ from the particle tracing: if a particle trajectory comes from the external border of the magnetosphere, its rigidity is above the cut-off, if comes from the Earth, it is below. This can be done using a code that reproduces the interaction of a charged particle with all the magnetic fields along the whole path.

The study of geomagnetic field and its interaction with charged particles in orbit around the Earth is developing very fast. Mainly due to recent data about intermagnetospheric magnetic fields and the sun interaction with the geomagnetic dipole new opportunities of studying the geomagnetic effects are provided.

Developed a code using internal magnetic field model IGRF 11 ([1]), and the latest external magnetic field models Tsyganenko 1996 and 2005([9]). This program (see [10]) has been optimized and adapted in order to analyse the data of the AMS experiment (see [11]), a magnetic spectrometer for cosmic rays that has been installed on the International Space Station in May 2011 during STS-134 Shuttle flight.

With this analysis it has been possible to investigate the composition of secondary and primary cosmic rays in the overall measured spectrum as a function of local geomagnetic and geographic positions. Our attention was especially focused on primary CR and the accuracy of incoming direction reconstructed outside of the magnetosphere for anisotropy study (see [12]).

### 2.1 Internal and External Field Models

The internal magnetic field model, IGRF 11, is a mathematical description of the Earth main magnetic field and its annual rate of change (secular variation). In source free regions this main field is the negative gradient of a scalar potential $V$, represented by a truncated series of spherical $(13^{th}$ order) harmonic expansion ([15]):

$$V(R, \theta, \lambda) = R_E \sum_{n+1}^{N} \sum_{m=0}^{n} \left( \frac{R_E}{R} \right)^{n+1} \left[ g_n^m \cos(m\phi) + h_n^m \sin(m\phi) \right] \cdot P_n^m(\cos(\theta)) \tag{2}$$

The so-called external magnetic field models, mainly developed by N. Tsyganenko, describes all the magnetic contributions originated outside the Earth surface. These can be charged particle currents, like the Ring current or magnetic interconnection fields, for example at the border of the magnetopause where the geomagnetic fields is shielding us from the Solar Wind.

The last and most updated Tsyganenko models are T96 [14] and T05 [15]. The first has been developed with a new set of measurements performed by different satellites, and includes all currents inside the magnetosphere (Birkeland regions, ring currents, tail currents, interconnection field and magnetopause field) plus external components included in T96 are also present here even if they depend on additional parameters and include additional components to reproduce measured data (for example the tail includes a fast and a slow component). These new 6 parameters, called W1 ... W6 have been fitted during the 37 major events of the 1996-200 period and depend only from 3 measured parameters as the Solar Wind density $N_{sw}$ and speed $v_{sw}$, and the southward interplanetary magnetic field $B$. We were able to obtain the external field parameters (for T96 they are) on a 5 minutes time base but for the AMS data analysis due to the large variations, especially for the Dst index, we chose to use as first step approximation the average hourly values of the four parameters (for T96) and the additional 6 parameters (for T05) for the whole period of the mission (Starting from May 2011 up to the end of 2012).

### 3 External or Not External

The CPU time ([10]) needed to estimate the external field with respect to the inner part is dominant (it depends on the particle position and direction but sometime can also be 10 times bigger), and there are differences even between the two external models, so T05 is almost 2 times slower than T96. The first question to be solved so is if an external field is needed. A macroscopic difference is that the IGRF representation of the geomagnetic field is essentially symmetric, while ([9]) the magnetosphere is highly asymmetric. This consideration can suggest the introduction of the external magnetic field. We anyway tested our backtracing code in different situations: excluding the external field (only internal one) or using both T05 and T96 models. As shown in Table 1 we backtraced a sample of $2.5 \times 10^8$ simulated protons between 0.3 and 200 GV at the ISS altitude and uniformly inside the AMS-02 field of view (45° from the zenith). Almost 20% of them are recognized as primary CR (allowed trajectories) only when traced back with the internal field, while they are not more primary CR when traced back with the complete (internal plus external) magnetic field. Most of this difference is located at high latitudes where the difference is close to 100%. Changing the external field model the difference is below 10%.

| Model         | IGRF      | IGRF + T96 | IGRF + T05 |
|---------------|-----------|------------|------------|
| IGRF          | 0%        | 21.5%      | 19.8%      |
| IGRF + T96    | 0%        | 9.5%       |            |
| IGRF + T05    | 0%        |            |            |

Table 1: Difference nature of particles - allowed or forbidden trajectory - with different magnetic field models

Then we restricted our analysis only on primary CR, so trajectories reconstructed by both models as allowed. In
this case the main question is how precise can be the reconstructed trajectory up to the border of the magnetopause. This question is related also to the magnetopause model and the mathematical precision of the code. As described elsewhere [10] our backtracing code, also in his “refurbished” version that has been included in the AMS official software, reconstructs a particle trajectory with an accuracy $< 10^{-3}$ (this is an upper limit occurring in particular cases, most of the times the precision is much better than this value). The evaluation of this accuracy takes into account all the parameters of the backtracing (time, altitude, direction), and is also related to the step size chosen. A fine tuning of each source of uncertainty, as described here [10], led to an optimization of the code, but every estimate will always have its intrinsic “error”, in relation to the fact that we reproduce a curved trajectory as a sum of infinitely small linear segments. Once everything is fixed (especially the magnetosphere model that has been chosen to be for both external field models the Shue one [18]) we evaluated the difference in final points for different rigidity bins (roughly speaking the curvature due to the two different magnetic field model). Our analysis was done on a sample of $2.2 \times 10^5$ electrons detected by AMS-02 in the period between June 2011 and September 2012. Primary particles has been divided in 4 rigidity bins: 20-30 GV, 30-40 GV, 40-50 GV and >50 GV (here we present only first and last bin). First of all we show in Fig. 1 and 2 the difference, separated in Latitude and Longitude between only IGRF internal field and External field T05. As can be clearly seen increasing the energy (in this case rigidity) the difference decreases. If we compare these plots with 3 and 4, where again are evaluated differences in the last points, but this time between the 2 external field models, we can see that not only is it reduced at high rigidity, but also in the bin 20-30 GV. This is an additional indication that the external field models are essential for this kind of study, and that they are also consistent.

![Figure 1: Latitudinal and Longitudinal difference of last point (magnetopause) for AMS-02 electrons in the rigidity range between 20 and 30 GV, for internal field IGRF and T05](image1)

![Figure 2: Latitudinal and Longitudinal difference of last point (magnetopause) for AMS-02 electrons for rigidity above 50 GV, for internal field IGRF and T05](image2)

Our study was focused on allowed trajectories and on the different entry point as reconstructed by backtracing (important in every case of direction study as for example anisotropy). As can be seen in Table 1 where we present the % of particles whose last point difference is greater than 0.5°, there is a significant difference between with and without the External field model. Moreover in Table 2 and 3 is also shown a reduction of the rms distribution both for Latitudinal and Longitudinal difference (higher this second one due to the “dipolar” structure of the geomagnetic field).

|                  | All | P<$4nPa$ | P>$4nPa$ |
|------------------|-----|---------|---------|
| Latitude NoExt-T05 | 10.9 | 10.3 | 18.2 |
| Longitude NoExt-T05 | 13.6 | 12.9 | 21.6 |
| Latitude T96-T05  | 3.5  | 3.3  | 6.7   |
| Longitude T96-T05  | 5.0  | 4.5  | 8.8   |

![Figure 3: Latitudinal and Longitudinal difference of last point (magnetopause) for AMS-02 electrons in the rigidity range between 20 and 30 GV, for external field models T96 and T05](image3)

![Figure 4: Latitudinal and Longitudinal difference of last point (magnetopause) for AMS-02 electrons for rigidity above 50 GV, for external field models T96 and T05](image4)

### 3.1 Tsyganenko 96 or 2005

Our study was then divided in two main groups, in relation to the Solar Wind pressure (the main indication of magnetic disturbances due to solar activity). This was one mainly because, as can be seen in Table 6 parameters for T05, recal-
Table 4: RMS of difference distribution (in mrad) - sample NoExt-T05 and T96-T05 - Bin > 50 GV

|                | All | P<4nPa | P>4nPa |
|----------------|-----|--------|--------|
| Latitude NoExt-T05 | 4.5 | 4.3    | 7.1    |
| Longitude NoExt-T05 | 6.9 | 6.7    | 10.6   |
| Latitude T96-T05   | 1.3 | 1.4    | 2.6    |
| Longitude T96-T05   | 2.3 | 2.2    | 3.7    |

Table 5: Percentage of particles with difference in last point greater than 0.5° - NoExt-T05 and T96-T05 - Bin >50 GV

|                | P<4nPa | P>4nPa |
|----------------|--------|--------|
| > 0.5° NoExt-T05 | 23.4%  | 22.1%  | 47.9%  |
| > 0.5° T96-T05   | 0.8%   | 0.6%   | 5.0%   |

Table 6: Missing parameters for T96 and T05 models, and % of recovered information using T96 below 4 nPa

|        | T96  | T05  | T96 no T05 |
|--------|------|------|------------|
| % missing | 1.5% | 14.8%|            |
| % fill   |      |      | 13.3%      |
| % fill (≤4 nPa) |      |      | 12.6%      |

4 Conclusions

We developed a code to reconstruct charge particle trajectory inside the geomagnetic field. This code has been implemented in the official software of the AMS-02 experiment in order to be used to separate primary and secondary CR. We evaluated the need for any kind of study (especially if related to the arrival direction of particles as for example anisotropy) to include the external field model, and we warmly recommend to use the last Tsyganenko 2005 model, developed for storm periods like that one in which AMS-02 is taking data. We applied our code to primary electron selected in more than one year of data and we suggested the possibility to use the Tsyganenko 1996 model to fill missing parameters for T05, when the Solar Wind pressure is below a certain limit, chosen as 2 times the average value.

5 Acknowledgements

We wish to especially thank Prof. N. Tsyganenko that provided us the new parameters for T05 model. This work is supported by Agenzia Spaziale Italiana under contract ASI-INFN I/002/13/0, Progetto AMS - Missione scientifica ed analisi dati.

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