PROCEEDINGS OF SCIENCE

Trajectory reconstruction in the Earth Magnetosphere using TS05 model and evaluation of geomagnetic cutoff in AMS-02 data.

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Our backtracing code (Geomagsphere), for Cosmic Rays trajectory reconstruction in the Earth Magnetosphere, has been developed using the latest models of Internal (IGRF-11) and External (Tsyganenko 1996 and 2005) field components. Backtracing technique was applied to AMS-02 data to separate Primary Cosmic Rays Particles from Secondary particles. We tested the accuracy of Magnetic Field models (with and without the external field component) comparing them with data from satellite (GOES, 1998 and CLUSTER, 2004). In both periods TS05 reproduces the magnetic field strength with good accuracy. Moreover the specificity of the TS05 model, designed for solar storms, was tested comparing it with data taken by CLUSTER during the last solar active period (from 2011 to 2013). We found a relevant difference on the fraction of AMS-02 cosmic rays identified as trapped and secondary particles, especially during solar flare periods (i.e. those occurred in March and May 2012). Finally the backtracing of a wide sample, more than 70 days, of AMS-02 proton data was used to get the real geomagnetic cutoff. We found an increased counting rate of primary particles at high latitudes with respect to the IGRF model. Besides we built a procedure to extract from data the rate of secondary particles.

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1. Introduction

We developed a software code for particle tracing to study the effect of the Earth magnetosphere on cosmic rays accessing the near Earth space, whose flux can be measured by detectors such as AMS-02 on board of the ISS since May 2011. Particles trajectories have been reconstructed using the internal magnetic field IGRF-11 [1] and the external magnetic field Tsyganenko 96 and 2005 [2, 3] to separate allowed and forbidden particle paths and thus distinguish between primary and secondary Cosmic Rays (CR). We focused our attention on the importance of including the external field in *backtracing* and we evaluated two field models, the first, Tsyganenko 96 (hereafter T96) developed for quiet geomagnetic periods, and the second, Tsyganenko 2005 (hereafter TS05) especially designed for storm events, with new data from 1996 to 2000 and we evaluated the effect of the external field on AMS-02 [4, 5] data during solar events.

2. Particle Tracing in the Geomagnetic Field

We can approximate the Earth magnetic field as a magnetic dipole, whose axis is shifted from the Earth center of $\sim 500\,km$, tilted of $\sim 11^\circ$ and opposite to the geographic rotational axis. The effect of the solar wind pressure is a compression of the magnetic field in the day-side and a decompressed in the night-side, creating a highly asymmetric magnetosphere configuration. Magnetic rigidity R, defined as the ratio between the momentum of the particle and its charge ($R = \frac{pc}{Ze}$), can be used to describe the effect of magnetic fields on charged particles, and in the Stormer[6] theory (dipolar approximation) we can define for every point in space a limit called *rigidity cut-off* [9], below which primary cosmic rays will never arrive.

$$R_{cut} \geq 59.6 \cdot \left[\frac{1 - \sqrt{1 - \cos^3 \vartheta_m \cdot \cos\gamma}}{\cos\vartheta_m \cdot \cos\gamma} \right]^2 \tag{2.1}$$

Where R_{cut} is in GV, ϑ_m is the magnetic latitude and γ is the angle between particle velocity and East-West geomagnetic direction (from East to West). With our analysis investigated the composition of secondary and primary cosmic rays in the overall measured spectrum as a function of local geographic positions. We focused our attention on the external field model accuracy in reproducing the measured magnetic field, and the effect on primary CR during solar active periods.

2.1 Internal and External Field Models

The internal magnetic field model is the mathematical description of the Earth main magnetic field and its secular variation, represented by the negative gradient (in source free regions) of a scalar potential V, that is by a truncated series of spherical (13^{th} order) harmonic expansion [13]:

$$\begin{aligned} V(R,\vartheta,\lambda) = R_E \cdot \sum_{n+1}^{N} \sum_{m=0}^{n} \left(\frac{R_E}{r}\right)^{n+1} \\ \cdot [g_n^m \cos(m\phi) + h_n^m \sin(m\phi)] \\ \cdot P_n^m \cos(\vartheta) \end{aligned} \tag{2.2}$$

We used external magnetic field models developed by N. Tsyganenko [10], they describe all the magnetic contributions originated outside the Earth surface as charge particle currents, or magnetic interconnection fields. We used last Tsyganenko models: T96 [14] and TS05 [15]. T96 has been developed with a new set of satellite measurements, and includes all magnetosphere currents plus a solar wind controlled magnetopause by Sibeck [16]. TS05 has been developed for storm events and fitted on 37 major events between 1996 and 2000, and depends on six more parameters called $W1$ ... $W6$, function of solar wind density N_{sw} and speed V_{sw} ,and the southward interplanetary magnetic field B_Z. In addition a different magnetopause model has been introduced due to Shue [17], where a new function has been estimated to evaluate the solar wind pressure effect on the magnetopause shape and size, and both the shape and compression due to the solar wind have changed with respect to Sibeck ones. For our study we used solar parameter values measured during 2011, 2012 and 2013 from OMNIWEB [7], TS05 web repository [8] or by N. Tsyganenko itself.

3. External Field Components

3.1 Magnetic Field Predictions vs. measurements

To evaluate the effective need of an external field model, we started to compare our model predictions with satellite measured values of the interplanetary magnetic field (IMF). Previous studies [20, 21] demonstrated that the developed models were reproducing better not only the IMF at various distances and, for example, the ring current, as in Ref. [21], but also that the modelled magnetosphere is taking into account transient phenomena due to the solar activity that the only internal field model IGRF can not reproduce as in Ref. [20]. Predictions were compared with CLUSTER [22] measurements, and then with the last TS05 in a period of a strong B_Z^{IMF} negative component with GOES-8 data, see Ref. [20]. Starting from these two previous work we performed some tests, comparing our model calculations with both CLUSTER for 2004 and GOES-8 data for 1998. As can be seen in Fig. 1 the agreement with IGRF+TS05 is much better that with the simple IGRF.

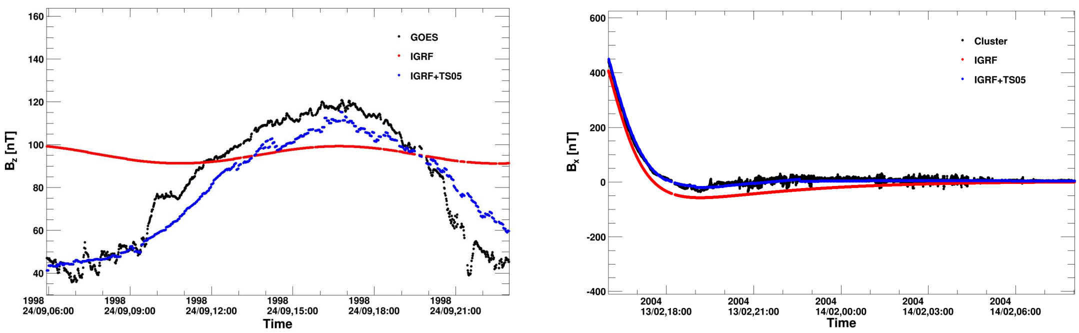

Figure 1: Cluster and Goes B field components calculation comparison with measurements

While they are similar at 1 R_E the asymmetry at 10 $R_E$related to the day/night compression from the solar wind is not reproduced by IGRF only (see Fig. 2).

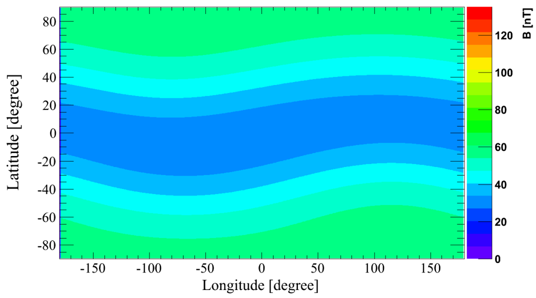

Figure 2: Magnetic field estimation at 10 R_E for IGRF only (left) and IGRF + TS05 (right).

We tested our backtracing code only with the internal field or using both TS05 and T96 models with a sample of 2.5×10^6 simulated protons. The result is that almost 20% of them show a different nature (forbidden vs allowed trajectories) if the external field is or not used. This overall difference is mainly located at high latitudes where its value is close to 100%. It is in average reduced below 10% changing the external field model, so TS05 and TS96. This difference is mainly related to solar active periods, in fact if we consider only quiet periods (i.e. $P_{dyn} \leq 4$ nPa) the difference is compatible within 2-3 %.

3.2 New Magnetic Field measeurements

We also performed a test of how precise could be our magnetic field model during AMS-02 data taking period. We chose again Cluster data, namely during 2011 (the beginning of AMS-02 mission) and 2012. The difference of magnetic field estimation with and without external field model is clearly in favour of using TS05 for all components (B_x, B_y and B_z). We evaluated the difference between measured and estimated field in two cases (only IGRF and IGRF plus TS05) and focused our attention on the average values as presented in Fig.3. As can be seen the difference absolute average value is always lower for TS05, and the RMS (not presented here) is roughly half of IGRF one (also if sometime comparable).

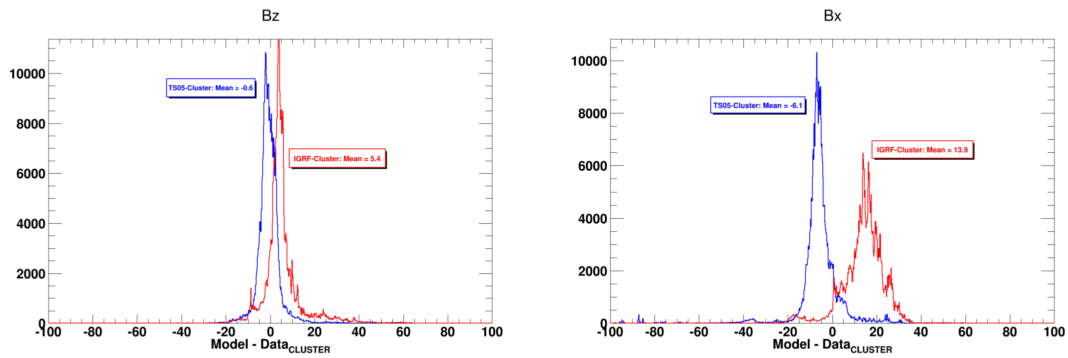

Figure 3: Total difference between magnetic field estimation with and without TS05 external field with respect to Cluster satellite measurements during the period 2011-2012 See [24]

4. Solar Flares analysis

Due to the special solar active period in which AMS-02 is taking data, and to the long duration of its mission (probably even over 2020) the possibility to study solar effects on CR particles led us to evaluate the geomagnetic response to such strong influence. We first analyzed the solar events from the beginning of the AMS-02 mission (May 2011) and focused our attention in flares of class X or M (see [25]). The two main periods we started to work on where March and May 2012, more precisely March 7 and May 17, where both flares were follwed by a CME (Coronal Mass Ejection) impact. We also found a correlation between the few days around the flare and the geomagnetic parameters, mainly the *Dst* index and the solar wind pressure P_{dyn}. The *Dst* parameter has its maximum (negative) value almost one day after the CME reaches the Earth, a signal that the magnetic disturbances need some time to propagate from the magnetopause down to the Earth surface. On the contrary the solar wind pressure P_{dyn} has its maximum value after the Flare, when the correlated CME is reaching the magnetopause border.

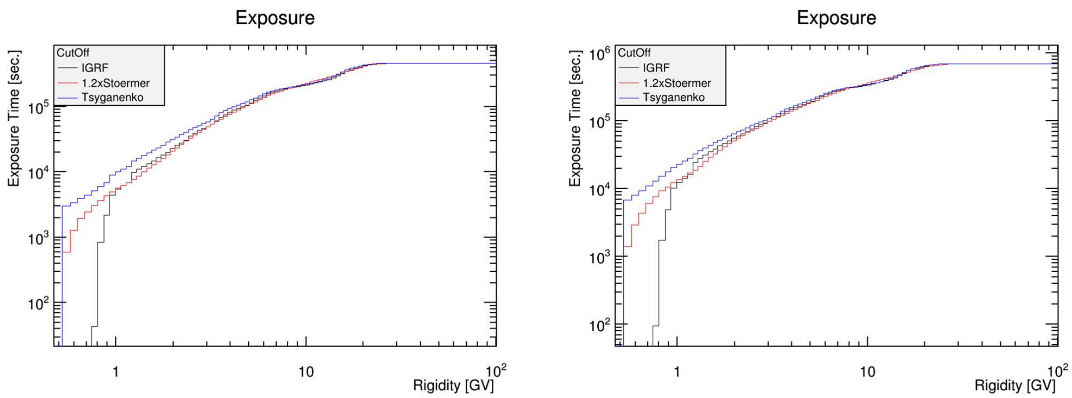

Figure 4: March and May Exposure time for AMS-02 with 3 different Rigidity Cutoff calculations See [26]

In order to separate primary and secondary CR we reconstructed all trajectories with our back-tracing code and compared the obtained results with other evaluated values obtained with the simple Stoermer formula [6] and only the IGRF model. Our external field model TS05 show a big difference in increasing the Exposure time (especially close to the magnetic poles see Fig. 4) due to the more precise evaluation of the magnetosphere response to highly disturbed situations as these intense solar flares are.

5. Rigidity cutoff calculation

The approach to estimate the geomagnetic rigidity cutoff from a selected location is through the reconstruction of CR trajectory back in time and reversing their incoming direction. In this way we can calculate the so-called Transmission Function (see [11]) for each detector location and field of view. It can be used to evaluate the primary particle rate for any experiment, so for a practical use only the upper (or maximum) cutoff should be used for primary CR analysis. In a symmetric way only the lower cutoff should be used for secondary CR analysis.

5.1 Primary and Secondary separation

We used the backtracing approach to analyze the AMS-02 data, and we decided to reconstruct the trajectory of detected protons in a wide range of time. Due to the huge amount of detected particles, we choosed randomly some days in the period 2011 (second half), 2012 and 2013, separated in 6 months slots with only two main requests: the first is that all the TS05 needed parameters exist in the validity range. Then we divided the geographic location of AMS-02 orbits in 2°x2° cells, and required a good coverage of all cells. The Rigidity cutoff we are able to evaluate with the direct bactracing of data are essentially two: the upper cutoff,later used also for the official AMS analysis [29], so the value above which for a selected location all particles are primaries, and the lower cutoff, so the value below which all detected particles are secondaries.

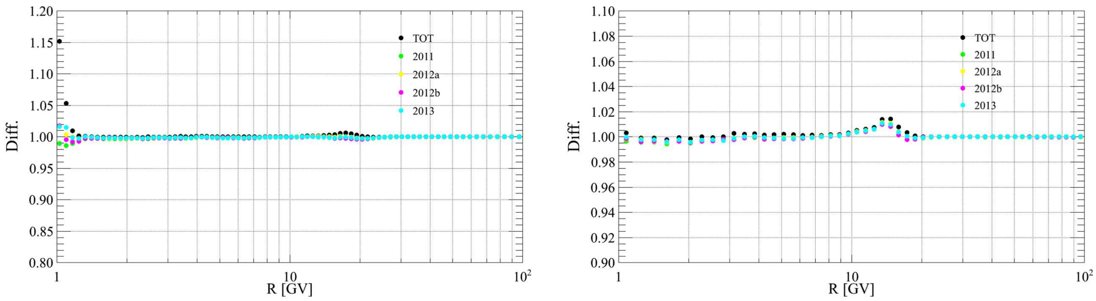

Figure 5: Particle rates for AMS-02 40° FOV (left) and 25° FOV (right): comparison of results obtained with two different Rigidity Cutoff calculations, IGRF only or IGRF + TS05

Once reconstructed the particle trajectories and separate allowed (primary CR) from forbidden ones (secondary CR), we evaluated the upper cutoff in each 2°x2° cell with the following formula:

$$R^{upper}_{cutoff} = \max(R_{Sec}) \tag{5.1}$$

where R_{Sec} is the rigidity of particles whose reconstructed trajectory correspond to a secondary CR. Above this value, if the statistics is enough (and with AMS-02 data and its 10^7 measured protons per day, we are quite confident), protons are only Primary. Then we evaluated the lower cutoff with the formula:

$$R^{lower}_{cutoff} = \min(R_{Pri}) \tag{5.2}$$

where R_{Pri} is the rigidity of particles whose reconstructed trajectory correspond to a primary CR, and, in a similar way as we discussed for R^{upper}_{cutoff}, below this value we have only secondaries.

A smoothing prcedure was later applied to avoid big differences between adjacent cells in this way: if the rigidity cutoff between the cell we are analizing and the following one (where the selection has been done in longitude) is greater than 10%, the new cell value is recalculated as the average value over all the adjacent cells (so in a square of 9 cells excluding the central one). As can be seen in Fig. 5 the overall rigidity cutoff with TS05 is only few % different from the IGRF only. This happens because of the large time range used to obtain an average value, if on the contrary a short period is considered, as specified for solar flares, the difference is not begligible (sometime even close to 100%)

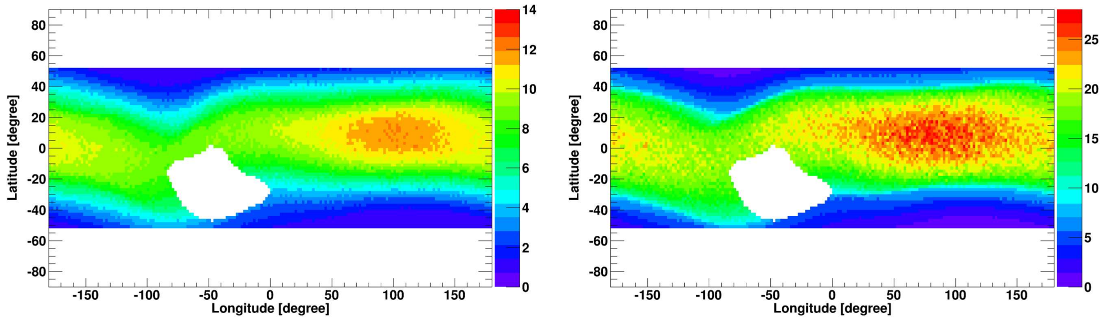

Figure 6: Map for Lower (left) and Upper (right) Rigidity cutoff for 40° FOV

6. Conclusion

We implemented in the AMS-02 software our code to reproduce particle trajectory inside the geomagnetic field to separate primary and secondary CR. We focused our attention on the external field model, and we compared our calculations also with satellite measurements strongly supporting to use the last Tsyganenko 2005 model, developed for storm periods like the AMS-02 data taking. Our code has been applied to protons data, both during special selected solar storms, and quiet periods, to calculate the rigidity cutoff. The accuracy of the external field model has been estimated comparing our predictions with measured satellite data. The main effect of using TS05 model is the increasing of exposure time at low rigidity, especially close to the magnetic poles, with a direct reduction of statistical errors on the measured flux.

Acknowledgments

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