Part 3. Impact of Solar wind, Structures and Radiation on Magnetospheres

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Comparison and Time Evolution of the Geomagnetic Cutoff at the ISS Position: Internal vs External Earth's Magnetic Field Models

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Abstract. Our back-tracing code (GeoMagSphere) reconstructs the cosmic ray trajectories inside the Earth's magnetosphere. GeoMagSphere gets the incoming directions of particles entering the magnetopause and disentangles primary from secondary particles (produced in atmosphere) or even particles trapped inside the Earth's magnetic field. The separation of these particle families allows us to evaluate the geomagnetic rigidity cutoff. The model can be used considering the internal symmetric (IGRF-12) magnetic field only, or adding the asymmetric external one (Tsyganenko models: T89, T96 or TS05). A quantitative comparison among these models is presented for quiet (solar pressure $P_{dyn} < 4$ nPa) and disturbed ($P_{dyn} > 4$ nPa) periods of solar activity, as well as during solar events like flares, CMEs. In this analysis we focused our attention on magnetic field data in magnetosphere, from Cluster, and simulated cosmic rays for a generic detector on the ISS as for example AMS-02. We found that high solar activity periods, like a large fraction of the period covering years 2011-2015, are better described using IGRF+TS05 model. Results, i.e. the average vertical rigidity cutoff at the ISS orbit, are shown in geographic maps of $2^\circ \times 2^\circ$ cells.

Keywords. Cosmic rays, Earth's magnetic fields, Sun activity

1. Introduction

Cosmic rays (CRs) arriving at Earth interact with the geomagnetic field. At the International Space Station (ISS) orbit, depending on the geographic position, a combination of primary, secondary and trapped particles is present; a quick description regarding these families can be found in e.g. Bobik *et al.* (2006). Primary particles are CRs arriving from the space outside the magnetosphere (the region affected by the Earth's magnetic field). Secondary particles, observed at ISS altitude ($\sim$ 400 km above the surface), are produced mainly by primary CRs interactions in the atmosphere. A fraction of secondaries can be trapped in it increasing the population of the radiation belts. Trajectories of charged particles inside the magnetosphere depend on particle velocities and magnetic field strength. For a specific geographic region and incoming direction it is possible to detect particles, depending on their rigidities, coming from outside the magnetosphere (primaries), from the atmosphere (secondaries) or from the radiation belts (trapped). At each rigidity it is possible to determine the origin of these particles. The transition between secondary+trapped particles and primary ones is not sharp and it is called

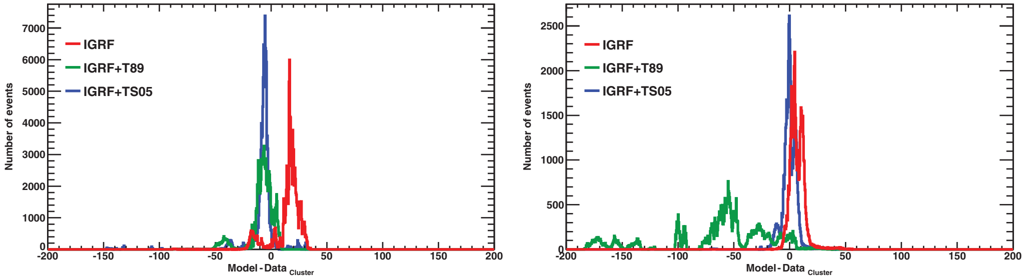

Figure 1. Amount of data as a function of the difference, regarding the component B_x of the magnetic field, between the model predictions (IGRF alone in red, IGRF+T89 in green and IGRF+TS05 in blue) and the Cluster satellite measurements during 2 - 7 November 2011 (left) and 5 - 9 March 2012 (right).

penumbra (see e.g. Cooke *et al.* 1991, Bobik *et al.* 2006). The rigidity value of the highest detected secondary particle is called *upper* (R_U) rigidity cutoff, above this value, only primary CR can reach the detector position. The rigidity value of the lowest primary particle is called *lower* (R_L) rigidity cutoff and, below it, only secondary (or trapped) particles can be detected, see e.g. Cooke *et al.* (1991). A method to establish the particle origin is to perform the so-called *back-tracing*, i.e. the reconstruction of particle trajectory back in time from the detector position up to the magnetopause (if particle is primary), or eventually the Earth's surface (in case of secondary particles).

2. GeoMagSphere model

The GeoMagSphere model (see e.g., GMS-website: http://www.geomagsphere.org/, Bobik *et al.* 2005, Bobik *et al.* 2006) performs the trajectory reconstruction inside the magnetosphere. Input parameters of the numerical code are: the particle mass and charge, its geographic position, time and arrival direction. Both particle charge and time are reversed for the back-tracing, in this way, as matter of fact, the propagation equation remains unchanged. GeoMagSphere adopts *IGRF* as internal magnetic field model (Finlay *et al.* 2010) and add an external magnetic field chosen among: *T89* (Tsyganenko 1989 and Peredo *et al.* 1993), *T96* (Tsyganenko 1995, 1996) or *TS05* (Tsyganenko and Sitnov 2005). The external border of the magnetosphere (the magnetopause) can be selected between the two models proposed by Sibeck *et al.* (1991) and Shue *et al.* (1997). One of the effects of adding the external field is to obtain an asymmetric magnetosphere as required by the interaction with the solar wind. A comparison between experimental magnetic field data, recorded by the Cluster satellite (Escoubet *et al.* 2001), and several models, with and without external field, is reported in Figure 1. The two periods selected are 2 - 7 November 2011 (left), considered quiet days without significant solar events, and 5 - 9 March 2012 (right) when large solar events (flare and CME) occurred. On the x-axis is reported the difference, regarding the component B_x of the magnetic field, between the model predictions and the experimental data. On the y-axis is reported the amount of data corresponding to that difference. The data analysed have a time bin of ~ 4 s corresponding to the Cluster data acquisition. In both cases magnetic field strength data are better described by IGRF+TS05 fields, in particular during March 2012, as expected since TS05 was specifically developed to reproduce the magnetosphere during magnetic storms. It is also shown that the differences between the IGRF+T89 and IGRF+TS05 models are mostly negligible during quiet periods (see also Grandi *et al.* 2015).

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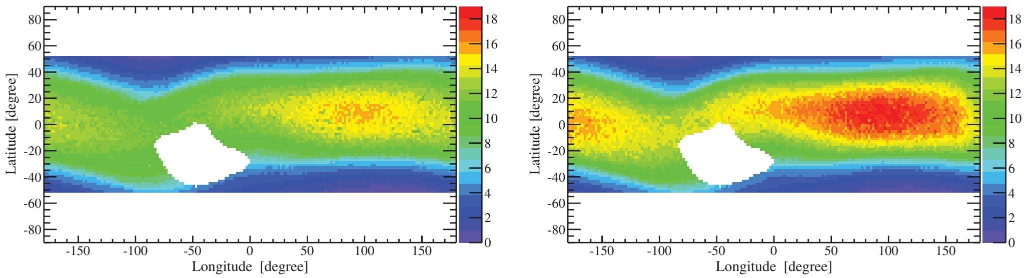

Figure 2. Average upper cutoff computed for the first six months of 2012 selecting particles arriving within 5° (left) and 20° (right) from the local zenith. The color scale represents the cutoff rigidity in GV. The white region in both maps is the South Atlantic Anomaly region excluded in this analysis.

3. Rigidity cutoff results

We then used GeoMagSphere, considering both IGRF and external fields, to evaluate the rigidity cutoff at the ISS orbit. Using TS05 as external field, we calculated R_{cut} for a given arrival direction (e.g., inside 5° from the local zenith), geographic position (e.g., at the ISS orbit) and time. We performed the back-tracing using the real time and position of the space station, considering simulated particles inside the acceptance cone of AMS-02 (Aguilar *et al.* 2015) (excluding the South Atlantic Anomaly region). We restricted our analysis to particles arriving inside a certain acceptance cone from the zenith at each given orbital position. We divided the geographic cutoff maps in $2° \times 2°$ cells and for each cell, the maximum rigidity for secondary (or trapped) particles identifies the upper cutoff (R_U). We analysed the cutoff widening the angle from the local zenith from 5° to 20°. In Figure 2 we reported the cutoff map regarding the first six months of 2012 selecting particles arriving within 5° (left) and 20° (right) from the local zenith. The white region inside the maps is the South Atlantic Anomaly as defined by the AMS-02 collaboration and, for this reason, excluded by the analysis. The magnetic latitudinal gradient is clearly shown. Figure 2 reports, as expected, that increasing the opening angle, more particles (e.g. secondaries with higher energy) can be observed in the detector, consequently the upper rigidity cutoff increase.

A time evolution of this cutoff was also calculated with a resolution of 6 months from July 2011 to June 2015. For each cell we evaluated the relative differences in R_U obtained in several time periods. The average differences, as a function of time, are inside $\sim 4\%$.

A deeper study was done on a specific day (i.e. March 7^{th}, 2012) where a large solar event occurred (see e.g., Della Torre 2016 and Di Fino *et al.* 2014). For this day we calculated the vertical cutoff using both IGRF+T89 and IGRF+TS05 models. The rigidity cutoff difference obtained by the two models was computed as a function of the geomagnetic latitude (λ_{mag}). For almost 90% of the observation time the difference between the two models is within 5%, while in the remaining 10% of the time, when the detector is close to the polar regions, this difference increases up to 70%.

4. Conclusions

We developed a code (GeoMagSphere) to reconstruct charged particle trajectories inside the geomagnetic field. GeoMagSphere is able to separate primary, secondary and trapped particles using a back-tracing technique. In this way, we are able to evaluate the rigidity cutoff. This procedure is mandatory in order to get the effective primary cosmic ray flux for every detector in space (we applied it to the magnetic spectrometer

AMS-02 on ISS). GeoMagSphere can be used considering the internal symmetric (IGRF-12) magnetic field only, or adding the asymmetric external one (Tsyganenko models: T89, T96 or TS05). We found that using IGRF+TS05 we can provide a better description of experimental data, both for magnetic field and cosmic ray fluxes, in particular in high solar activity periods. We evaluated the upper cutoff as a function of the opening angle with respect to the local zenith and we observed higher rigidity cutoffs correlated to higher angles. Rigidity cutoff maps, in geographic coordinates, where computed every 6 months and the average differences among them, as a function of time, are inside $\sim 4\%$.

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