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Simulation of the geomagnetic cut-off with GEANT using the International Geomagnetic Reference Field

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Abstract. The International Geomagnetic Reference Field is used in a GEANT3 simulation to calculate the geomagnetic cut-off for cosmic rays entering in the Earth's magnetic field. The calculations are done in the back tracking method, where antiprotons start from the top of atmosphere and are tracked to outer space. The geomagnetic cut-off functions are estimated in momentum steps of 0.2 GeV for 131 directions in 1655 locations covering in a nearly equidistant grid the surface of the Earth. For special locations, where neutrino or low energy muon data have been measured, the cut-off functions are calculated in a fine grid of 21601 directions. The estimated geomagnetic cut-offs can be verified by the experimental results for primary protons and helium nuclei measured in different geomagnetic latitudes during the shuttle mission of the AMS prototype. These precise tables of the geomagnetic cut-off can be used in the frame of the CORSIKA code to calculate atmospheric muon and neutrino fluxes.

1 Introduction

A precise knowledge of the geomagnetic cut-off is a substantial ingredient to any calculation of low energy particle fluxes in the Earth's atmosphere. Especially the calculation of atmospheric neutrino fluxes for the investigation of the Atmospheric Neutrino Anomaly, requests precise, directional dependent tables of geomagnetic cut-off functions. In case of the Super-Kamiokande experiment in Kamioka, Japan, which delivers the most precise results on the Atmospheric Neutrino Anomaly (Fukuda et al., 1998), exist substantial differences between neutrinos produced above the detector and the neutrinos produced in the antipode region in the South Atlantic. This observation is commonly interpreted as clear evidence for neutrino oscillations.

Nevertheless there are also geographical differences between Japan and the South Atlantic which have to be taken in consideration. Due to the South Atlantic Magnetic Field Anomaly the geomagnetic cut-off in Japan is about 50 % higher than at the opposite point of the Earth. In addition, the experimental observation of a directional East-West dependency of the neutrino fluxes (Futagami et al., 1999) has to be accounted mainly to the asymmetry in the primary particle flux caused by the geomagnetic cut-off, while the deflection of charged secondary particles, like pions and muons in the atmosphere plays a minor, but not negligible role.

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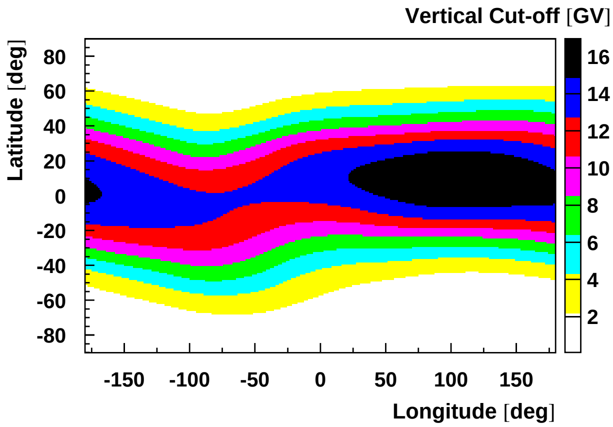

Fig. 1. World map of the vertical geomagnetic cut-off for an altitude of 112.3 km.

2 The back tracking method for the calculation of the geomagnetic cut-off

The simulation of the geomagnetic cut-off is done in a complete microscopic calculation of possible proton trajectories in a realistic magnetic field for the Earth.

In principle there exist only four different types of particle trajectories:

– Start and end point of the trajectory are outside of the Earth's magnetosphere.

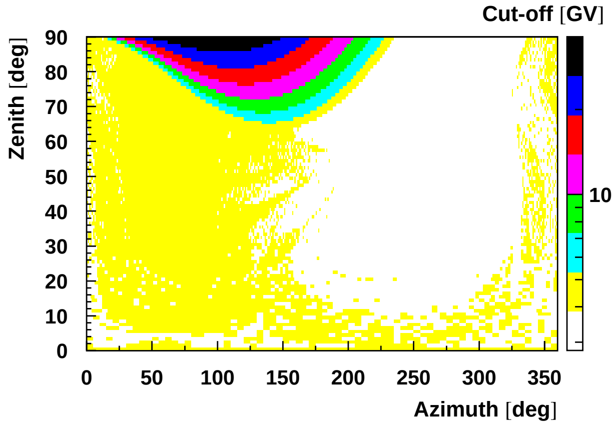

Fig. 2. The directional dependence of the geomagnetic cut-off for Fort Sumner, New Mexico (34.3° North, 104.1° West). The counting of the azimuth angle ϕ follows the convention used by the Super-Kamiokande detector, $\phi = 0°$ means looking to the South, $\phi = 90°$ to East, etc.

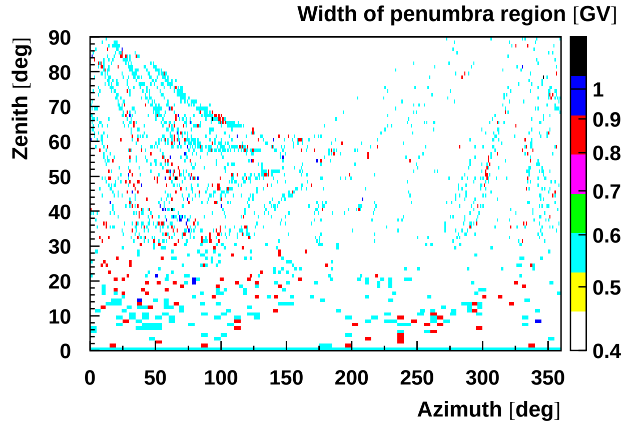

Fig. 3. The width of penumbra region, i.e. the difference between the open trajectory of lowest and the closed trajectory of highest momentum for Fort Sumner.

– The trajectory is enclosed in the magnetosphere, meaning that neither the Earth's surface nor the space outside the magnetosphere is reached ever.

– Start and end point of the trajectory are on the Earth's surface.

– The trajectory connects the outer space with the Earth's surface.

Only the trajectories of the last category represents particles above the geomagnetic cut-off. Thus the simulation of the geomagnetic cut-off can be reduced to the problem of calculating these trajectories. Due to the possibility of inverting the problem, the calculation of the geomagnetic cut-off can be done in the back tracking method, where antiprotons start from the Earth's surface and are tracked until they reach outer space, where the magnetic field vanishes, or they are bend back to the Earth.

Assuming an isotopic primary flux in outer space, which is only disturbed by the presence of the Earth and its magnetic field, the directional particle intensity can be calculated by taken out all forbidden trajectories, expressed in a table of the geomagnetic cut-off, depending on the geographical position, the local arrival direction and the momentum of the particle. This is a direct consequence of applying Liouville's theorem, as has been proved already by Lemaitre and Vallarta (1933) and Störmer (1930).

As starting altitude of the back tracking method, the top of atmosphere in an elevation of 112.3 km is selected. This particular choice of the starting altitude allows the direct use of the results within the CORSIKA simulation program (Heck et al., 1998). The magnetic field inside the Earth's atmosphere and the deflection of charged particle in it is handled in CORSIKA. CORSIKA is a code widely used for the simulation of extensive air showers. The extension by the tables of the geomagnetic cut-off allows now the simulation of low energy primary particles, too.

The antiprotons are tracked with the GEANT3 detector simulation tool (CERN, 1993). Due to the unusual dimensions for a GEANT simulation, the tracking precision has to be investigated. The tracking can be tested by reversing the trajectory, meaning that the momenta and charge of the antiproton are inverted, after the particle leaves the magnetosphere and the reversed particle is traced on its way back to the starting point. The error found by this method is some 10 m. Compared with an track length of typically 50000 km, this means a relative tracking error of $2 \cdot 10^{-7}$.

The Earth's magnetic field is described by the International Geomagnetic Reference Field (IAGA, 1992) for the year 2000. This allows a precise simulation of the penumbra region, too. While a pure dipole field leads always to a sharp cut-off, the precise irregular field with its inhomogeneities shows partly a diffuse region between the closed trajectory of highest and open trajectories of lowest momentum.

3 Calculations and results for the geomagnetic cut-off

For a world survey, geomagnetic cut-off functions have been simulated for 1655 locations, distributed nearly equidistant over the Earth's surface. The functions are simulated in 320 momentum steps for a momentum range between 0.4 and 64.4 GeV for 131 arrival directions. The momentum range covers all energies from the particle production threshold up to the maximum cut-off of a particle impinging horizontally at the geomagnetic equator from the East.

The simulation of the complete cut-off functions in fixed momentum steps allows to study the smoothness of the cut-off, the sometimes chaotic behavior of the cut-off in some regions and the existence of gaps for the primary protons well below the geomagnetic cut-off. The chosen resolution of 0.2 GeV/c is sufficient for the goal of the calculation of atmospheric particle fluxes. The obtained world map of the

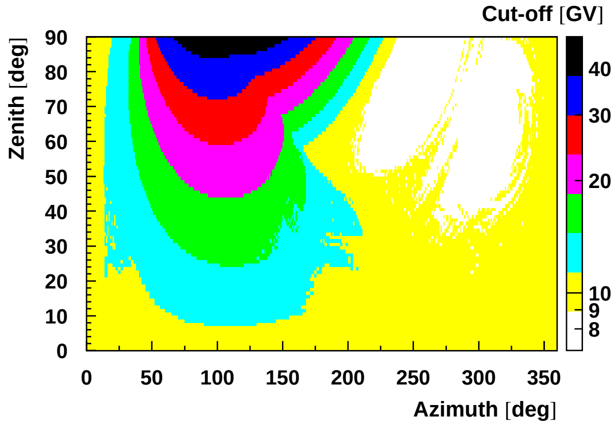

Fig. 4. The directional dependence of the geomagnetic cut-off for Kamioka (36.4° North, 137.3° East).

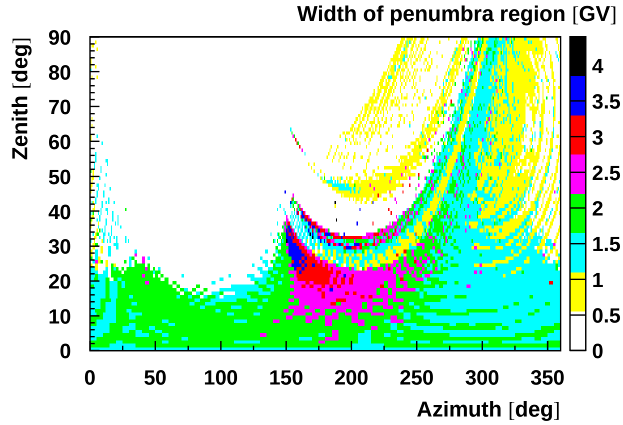

Fig. 5. The width of penumbra region for Kamioka site. Large values, i.e. bigger than 2 GeV indicate usually gaps in the cut-off.

vertical geomagnetic cut-off rigidity is shown in Fig. 1.

For some selected places, where experimental results exist for low energy muons or atmospheric neutrinos, precise tables of the geomagnetic cut-off with an angular resolution of 250 μsr have been calculated. As an example, the directional dependence of the geomagnetic cut-off for Fort Sumner in New Mexico is presented in Fig. 2. Fort Sumner has been used by many balloonborne detectors as launching place. Fig. 3 displays the sharpness of the cut-off, defined by the momentum difference between the first open and the last closed trajectory. In case of Fort Sumner the cut-off is relatively sharp, especially for directions with a higher cut-off the penumbra region is rather narrow or not found at all.

Fig. 4 shows the directional dependence of the geomagnetic cut-off for Kamioka. Remarkable is the strong deviation from a regular shape as observed in the calculation for Fort Sumner (Fig. 2) caused by some local irregularities of the magnetic field over Japan. This feature should be reflected in the azimuthal dependence of the particle intensity in Kamioka.

Interesting is the broad penumbra region in Kamioka. As can be seen in Fig. 5 the penumbra region has a width of more than 4 GV in some cases. This is about 4 times broader than in the calculation for Fort Sumner, while the maximum cut-off in both locations is practically comparable. Also the existence of cut-off gaps, meaning windows for primary protons some GV below the actual cut-off is observed.

Especially in the region around a zenith angle of 25° and an azimuth angle of 160° this effect is very pronounced and explains the chaotic behavior observed in the geomagnetic cut-off map. This feature is the result of higher order corrections of the magnetic field in this direction and can be accounted only in a detailed calculation, like the one presented here. Usual calculations with a pure dipole field used in many simulations of atmospheric particle fluxes fail completely in reproducing this effect. Due to the steep spectra of primary cosmic rays, the contribution of primary protons from such a gap may have a significant contribution to the neutrino flux from this direction.

4 The AMS results for the geomagnetic cut-off

Recently the geomagnetic cut-off was measured with high precision by the space shuttle mission of the AMS-prototype (Alpha Magnetic Spectrometer) (Alcaraz et al., 2000, 2001). Due to the inclination of 51.7° of the shuttle orbit, the shuttle passes geomagnetic latitudes from 0 to more than 1 rad. The experimental spectra of downward going protons and helium nuclei can be compared rather directly with the results of this simulation. Only a small correction in the order of 10 % for the difference in altitude between the top of atmosphere as assumed in CORSIKA and the shuttle orbit is applied.

In detail, the position of the shuttle and the detector acceptance are taken into account. Locations situated in the region of the South Atlantic Magnetic Field Anomaly are excluded, as they are in the published values of AMS. The primary isotropic spectra are simulated following the measured exponential energy spectra but being extrapolated downward to $E = 0$. The solar modulation is assumed to follow the parameterization of Gleeson and Axford (1968). Particles above the geomagnetic cut-off and being inside the detector acceptance are sorted out and compared with the measured spectra.

The spectra of primary protons for different regions of the geomagnetic latitude together with the simulation results are shown in Fig. 6, while Fig. 7 displays the corresponding results for primary helium nuclei. The lower flux of primary helium allows only the subdivision in 3 intervals of the geomagnetic latitude.

The excellent agreement of the actual cut-off calculation with the experimental results shows the high precision of the calculation, only the proton spectrum for geomagnetic latitudes $0.9 < \theta_{mag} < 1$ shows a slight difference, which has to be attributed to the smallness of the cut-off value which is more or less equal to the momentum steps of the cut-off functions. This disagreement has not any influence on the

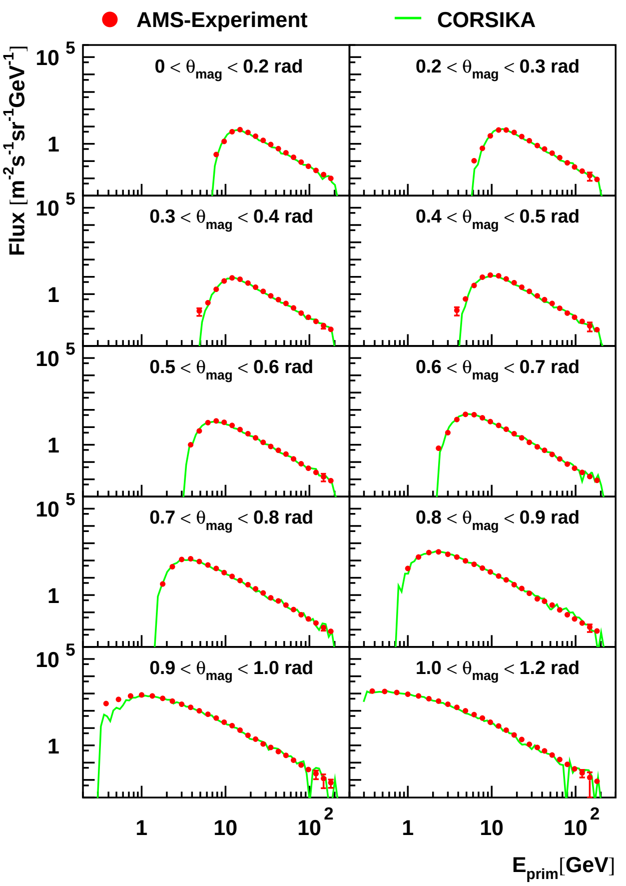

Fig. 6. Comparison of the AMS-results on primary protons for different intervals of the geomagnetic latitude with the results of the simulation of the geomagnetic cut-off.

simulation of atmospheric neutrino and muon fluxes, because the involved energies are already near the particle production threshold and the produced secondary particles hardly reach the Earth's surface with a valuable energy.

5 Conclusions

By using the International Geomagnetic Reference Field and the GEANT3 detector simulation tools, a program for simulating geomagnetic cut-off functions for primary cosmic ray particles at the top of the atmosphere was developed.

This program has been used to calculate a world wide table of geomagnetic cut-off functions for the epoch 2000 in momentum steps of 0.2 GeV/c, where the directional dependence is taken into account by simulating 131 different directions at any of the 1655 points on the Earth's surface.

The results of the calculation can be verified by the new results of the prototype of the AMS experiment. The measured spectra of primary protons and helium nuclei show a perfect agreement with the calculated values of the geomagnetic cut-off.

For selected locations on the Earth, where experimental

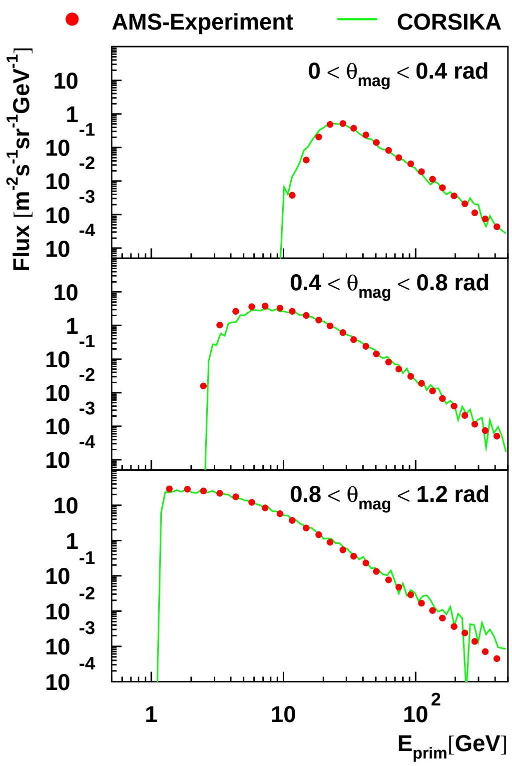

Fig. 7. Comparison of the AMS-results on primary helium nuclei with the results of the simulation of the geomagnetic cut-off.

results for low energy atmospheric neutrino or muon fluxes have been measured, detailed calculations in 21601 directions for the geomagnetic cut-off have been performed. The resulting cut-off tables have been used for the simulation of atmospheric muon fluxes and the simulation of the neutrino fluxes for Super-Kamiokande site with CORSIKA (Wentz et al., 2001).

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