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Geant4 software application for the simulation of cosmic ray showers in the Earth's atmosphere

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HIGHLIGHTS

- A new Geant4 software application-DYASTIMA- is presented.
- It can be used for the simulation of atmospheric showers caused by cosmic rays.
- It is an easy to use application and can fit to a variety of other applications.
- It can easily be parameterized in several parts.
- It fits many needs, as the cosmic ray spectrum, the atmospheric structure and the magnetic field.

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ABSTRACT

Galactic cosmic rays and solar energetic particles with sufficient rigidity to penetrate the geomagnetic field, enter the Earth's atmosphere and interact with the electrons and the nuclei of its atoms and molecules. From the interactions with the nuclei, cascades of secondary particles are produced that can be detected by ground-based detectors such as neutron monitors and muon counters. The theoretical study of the details of the atmospheric showers is of great importance, since many applications, such as the dosimetry for the aviation crews, are based on it. In this work, a new application which can be used in order to study the showers of the secondary particles in the atmosphere is presented. This application is based on the Monte Carlo simulation techniques, performed by using the well-known Geant4 toolkit. We present a thorough analysis of the simulation's critical points, including a description of the procedure applied in order to model the atmosphere and the geomagnetic field. Representative results obtained by the application are presented and future plans for the project are discussed.

1. Introduction

Galactic cosmic rays (GCRs) are particles that originate from stellar sources and are accelerated to high energies. They consist mainly of protons (∼89%), alpha particles (∼10%) and a small portion (∼1%) of heavier nuclei. The energy spectrum of the cosmic rays is wide, ranging from about 10^9 eV to extremely high energies of about 10^{21} eV. However, the flux of the particles decreases rapidly as their energy increases; hence, common cosmic rays have energies from about 1 GeV to a few hundreds of GeV (Gaisser et al., 2001). The magnetic field of the Earth provides shielding of the planet from the cosmic ray particles. Depending on their rigidity, cosmic rays penetrate the magnetic field of the Earth and reach the top of the atmosphere (Smart et al., 2000). The insertion and penetration of cosmic rays in the Earth's atmosphere depend on the particle energy and incident velocity direction and are highly related to the solar activity. The solar wind conditions at 1 AU from the Sun, modulate the Earth's magnetic field and often modify the magnetic cut-off rigidity as well, allowing the entrance of lower energy particles in the atmosphere. Furthermore, during periods of intense solar activity, manifested by coronal mass ejections (CMEs) and solar flares, the cosmic ray flux at the vicinity of the Earth can be enhanced. This is due to solar energetic particles (SEPs) which arrive at the Earth and have a composition similar to that of the galactic cosmic rays and energies from a few keV to a few GeV (Miroshnichenko, 2001). These particles are also known as Solar Cosmic Rays (SCRs) and sometimes lead

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to Ground Level Enhancements (GLEs), where an increase of cosmic ray intensity is detected at ground level (Belov et al., 2005; Plainaki et al., 2005, 2007). However, the intense solar activity may often have the opposite result, reducing the galactic cosmic ray flux for 1 week and more, leading to Forbush decreases (Lockwood, 1971; Papaioannou et al., 2009).

As the cosmic ray particles enter the atmosphere, they interact with the electrons and the nuclei of its atoms and molecules and secondary particles are generated. These secondary particles interact further, through several processes, such as elastic and inelastic scattering, decay, pair production, annihilation, Compton scattering, photoelectric effect, ionization, Bremsstrahlung radiation and Cherenkov radiation. The result is showers of muons, neutrinos, electrons, positrons, gammas, as well as neutrons, protons, π+ and K+ (Dorman, 2004; Longair, 2011). Secondary cosmic rays are continuously monitored by ground-based detectors. Neutron monitors measure the hadronic component of the secondary cosmic rays (http://www.nmdb.eu), muon counters measure the muonic component, while Cherenkov detectors register the Cherenkov radiation produced by the passage of high energetic charged particles through the atmosphere. The study of the secondary particle showers is of great importance, since it provides a correlation between the secondary cosmic rays that are measured by the ground based detectors and the primary cosmic rays at the top of the atmosphere. This correlation is of particular importance, when ground-based measurements are used as inputs for space weather applications. Moreover, the study of the atmospheric showers contributes to the determination of the affection that the barometric pressure and the temperature have on the hadronic and the muonic cosmic ray components respectively (Kobelev et al., 2011; Paschalis et al., 2013a). The determination of the relation between barometric pressure/temperature and cosmic ray flux registered at ground-level is also very useful in the primary processing of the ground based detectors data. Finally, an important application of the cosmic ray showers study is the calculation of the radiation dose to which aircraft crews are exposed (Bütikofer and Flückiger, 2011).

An efficient way to study the cosmic ray showers is via Monte Carlo (MC) simulations, which are very useful tools for the representation of several physical phenomena. The MC simulation technique has been used several times in cosmic ray studies. Many of these studies make use of the well known FLUKA (Battistoni et al., 2007; Ferrari et al., 2005) and Geant4 (Agostinelli et al., 2003; Allison et al., 2006) simulation toolkits. The operation and the detection efficiency of the neutron monitors have been studied for several cases and from various aspects (Balabin et al., 2011; Maurchev et al., 2011; Semikh et al., 2012; Paschalis et al., 2013b). The interactions of cosmic ray particles with the matter of the Earth's atmosphere have also been studied via simulations (Battistoni et al., 2003; Desorgher et al., 2003), while the development of the CRII model which calculates the cosmic ray induced ionization in the atmosphere, is very important as well (Usoskin et al., 2004, 2010; Usoskin and Kovaltsov, 2006). The response and the yield function of a neutron monitor have also been investigated several times, with the MC simulation of the cosmic rays propagation through the atmosphere and their detection by the neutron monitor (Debrunner et al., 1982; Clem, 1999; Clem and Dorman, 2000; Flückiger et al., 2008; Matthiä et al., 2009; Mishev et al., 2013). Apart from these works, very important is the development of standalone programs for the simulation of the cosmic ray interactions with the matter of the atmosphere. Heck et al. (1998) have developed CORSIKA while a similar application, based on Geant4, is the ATMOCOSMICS (Desorgher et al., 2005). The ATMOCOSMICS is usually combined with MAGNETOCOSMICS, based also on Geant4, which determines the transport of the cosmic ray particles in the Earth's magnetosphere. Finally, PLANETOCOSMICS combines and extends MAGNETOCOSMICS and ATMOCOSMICS in order to study the propagation of the cosmic rays in several planets, such as Earth, Mars and Mercury (Desorgher et al., 2006; Dartnell et al., 2007; Gurtner et al., 2007).

In this work, the first version of a Dynamic Atmospheric Shower Tracking Interactive Model Application (DYASTIMA) for the simulation of cosmic ray showers in the atmosphere based on the Geant4 toolkit (Agostinelli et al., 2003; Allison et al., 2006), is presented. Two aims were primarily taken into account during the implementation of DYASTIMA. The first one was the development of an application, which can be easily parameterized in several points, in order to adapt to different conditions of atmospheric structure, magnetic field and primary cosmic ray spectrum. The second one was the provision of multiple output information in such a format that its direct insertion in several applications will be possible. This work is organized as follows: in Section 2 the model description is presented. In Section 3, we give some representative results and discuss their utility in other space weather applications. In Section 4, the main conclusions of this work and some future ideas are discussed.

2. Implementation steps

The implementation of DYASTIMA consists of three main parts: (a) the modeling of the environment that affects the cosmic ray showers, in such a manner, that the user can adapt it to his simulation scenario, (b) the determination of the simulation scenario in Geant4 and the use of the Geant4 for the simulation of the actual cascade and (c) the output of the simulation results, in such a way as to be easily used by a variety of applications. Geant4 is a well known simulation package written in C++ that was initially developed for the simulation of high energy physics and gradually got enhanced, in order to be applied to lower energies. The package provides a huge variety of options and great support through the official and unofficial web communities (http://geant4.cern.ch; http://hypernews.slac.stanford.edu/HyperNews/geant4/cindex). For all these reasons Geant4 is currently used for a variety of applications, not only in high energies (Banerjee et al., 1999; Costanzo et al., 2006; Apostolakis et al., 2008), but also in nuclear physics (Kaitaniemi et al., 2010; Heikkinen et al., 2010) and in medical physics (Rodrigues et al., 2004; Canadas et al., 2011). In the field of cosmic rays research, Geant4 has also been used as was mentioned in the introduction. In the following paragraphs, we describe the modeling of DYASTIMA, its implementation steps and its usage critical points.

2.1. Modeling

In order to implement a simulation of the cosmic ray propagation through the atmosphere, the following physical quantities and processes that affect the simulation should be modeled first:

- the spectrum of the primary cosmic rays that reach the top of the atmosphere
- the structure of the atmosphere
- the Earth's magnetic field
- the physics interactions that take place between the cosmic ray particles and the molecules of the atmosphere

These quantities are affected by various parameters, such as the space weather conditions, the current physical characteristics of the Earth's atmosphere, the time and the location for which the simulation is performed.

Apart from the physics of the interactions of the cosmic ray particles with the matter of the atmosphere that is described in the