Modelling of the Cosmic-Ray Induced Gamma-Ray Emission of the Earth’s Atmosphere

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Abstract: Interactions of cosmic rays (CRs) with the Earth’s atmosphere produce X-rays and γ-rays, and other secondary particles (secondary nuclei, neutrons/anti-neutrons, protons/anti-protons, and electrons/positrons) that are a strong background for balloon-borne and space-based instruments. Indirect searches for particle dark matter in CRs, measurement of CRs and their modulation over the solar cycle, etc., crucially rely on understanding the secondary particle fluxes generated by the primary CR interactions in the atmosphere. Modelling the CR-induced γ-ray emission of the atmosphere provides the most useful method to understand these particle backgrounds, because a direct test can be made with observations without additional modelling and assumptions for the transport of charged CRs in the geomagnetic field. In this paper, we describe our modelling of the CR-induced γ-ray emission from the Earth’s atmosphere using the GEANT4 Monte Carlo code. We compare our model with the γ-ray data from the Fermi–LAT and other instruments.

Keywords: astroparticle physics — elementary particles — cosmic rays — diffuse radiation — gamma rays: ISM

1 Introduction

Observations of the CR-induced atmospheric γ-ray emission have a long history, starting in the 1960s first on balloons and, later, also on spacecraft [1, 2, 3, 4, 5, 6, 7, 8, 9]. Observations of the CR-induced atmospheric γ-ray emission were made by the EGRET instrument onboard the CGRO [10]. EGRET collected ∼ 5.2 million photons over its mission lifetime; roughly 60% of these were from the Earth disk. Recently, the Fermi–LAT collaboration has reported measurements of the CR-induced γ-ray emission from the Earth’s atmosphere [11]. These data are a significant improvement over the EGRET observations in both statistics and energy range covered. The spectrum measured over many orbits during the Launch and Early Operations (L&EO) period, and during a dedicated limb-following data-taking run, is ∝ E γ−2.79±0.06 in the range 3–500 GeV, thus showing the potential for on-orbit checking of the instrument performance up to the highest energies. However, in the energy range ∼ 5–15 GeV, where no departure from a power-law is expected, the Fermi–LAT-measured spectrum shows a feature (see Fig. 2 of [11]). Even though this is within the quoted systematic error, the smoothly-varying nature of the feature raises the question of its origin, be it an artifact of the analysis, an error in the effective area or energy resolution, or due to the physics of CR interactions in the atmosphere. Comparison between the Fermi–LAT-measured spectrum and intensities, and the EGRET-based model of the atmospheric γ-ray emission [10] shows significant discrepancies: the Fermi–LAT-measured profiles are much sharper at high energies and have significantly lower levels of emission, particularly toward the inner part of the Earth disk.

Modelling the CR-induced γ-ray emission is the most useful method to understand these particle backgrounds because a direct test can be made with observations; understanding the other charged secondary species requires additional modelling and assumptions for the transport of the particles in the geomagnetic field. Furthermore, comparison between model and data for the CR-induced atmospheric γ-ray emission provides valuable information about the development of CR cascades in the upper atmosphere and thus enables testing theoretical predictions of the production of secondary particles in CR interactions.

The CR-induced emission also provides an important source of calibration photons for a γ-ray instrument such as the Fermi–LAT. The high-energy CRs, mainly protons and alpha particles, interacting in the upper-most layers of the atmosphere produce a γ-ray spectrum with the same spectral shape as the primary particles. Because the CR primary spectra are well-measured and smoothly varying power laws (typically ∝ E−2.7 − E−2.8), the atmospheric γ-ray spectrum provides an on-orbit calibration check of the effective area and energy resolution: the corresponding γ-ray spectrum should also be smooth, so errors will manifest as features in the measured γ-ray spectrum, or an incorrect spectral index.
2 Modelling

Models have come a long way from early, rough estimates [12, 13, 14, 15], to sophisticated Monte Carlo codes, e.g., GEANT4 [16] that are based on detailed descriptions of all physical processes involved. The most detailed simulations of the atmospheric high-energy photon production have been made in the X-ray and soft γ-ray range [17, 18, 19] and at multi-TeV energies [20], while for intermediate energies MeV–TeV no detailed model exists.

Cosmic-ray primaries, mainly protons and alpha particles, interact in the atmosphere, producing a cascade of secondary particles (γ-rays, electrons/positrons, protons/antiprotons, neutrons, etc.). The CR primary intensities and spectra vary with the solar cycle (the so-called “heliospheric modulation”), as does the atmospheric profile. In addition, the geomagnetic field slowly varies with time. The CRs are affected by the geomagnetic field such that their intensities and spectra in near-Earth orbit are different from interplanetary space. These effects need to be taken into account for any accurate calculation for the atmospheric γ-ray emission.

The geometry of the γ-ray production in the Earth’s atmosphere is shown in Fig. 1 where the atmosphere size relative to the Earth is exaggerated. The γ-ray emission at any point in the atmosphere is due to the integrated contribution by CR showers developing through a range of column densities of atmosphere. At the detector, the measured γ-ray intensity is the line-of-sight integration through the atmosphere of all such points, taking into account the attenuation of the γ-rays during transmission through the atmosphere. The atmospheric profile is therefore important and we use detailed atmospheric models, such as NRLMSISE-00 [21] that provide the most realistic density profiles up to an altitude of 500 km, in our calculations.

The high-energy γ-ray emission (above ∼ 2 – 3 GeV) that is measured by an instrument on-orbit comes from CR showers developing essentially tangentially through the atmosphere along the line-of-sight toward the detector, while lower energy emission comes from all points in the atmosphere. It is only in the upper layers of the atmosphere where the CRs interact in the “thin target” regime (essentially through a column density < 10 g cm⁻² toward the detector) that the high-energy emission is produced. For higher interaction column densities, the CR interactions progressively approach the “thick target” regime where also significant attenuation of the γ-ray emission occurs. The use of a Monte Carlo method to treat these different regimes is necessary and we modified our GEANT4-based code from [22] to simulate CR-interactions in a gaseous atmosphere. Our Monte Carlo code includes the production of all secondary particles in the interaction, and gives the combined γ-ray emission from the prompt production (of π⁰’s in the first interaction), along with the emission from subsequent cascading and energy losses of, e.g., e± also produced in the showering. This method is capable of treating the CR-target interactions over a wide range of column densities. As an example, the development of a 100 GeV proton shower through 1 g cm⁻² of “Earth atmosphere” (composition: 75.5% nitrogen, 23.2 % oxygen, and 1.3% argon by weight) is shown in Fig. 2. This illustrates how the highest-energy γ-rays are produced collinear to the shower axis in the “forward” direction (cos θ = −1). Only low-energy (< 1 GeV) γ-rays are produced in the “backward” direction (cos θ = 1). It is straightforward to see that the...
The variation in intensity with azimuthal angle causes the so-called “east-west” effect seen in the Fermi–LAT-measured Earth disk emission (Fig. 5 of [11]).

viewing geometry is the reason that only high-energy γ-rays come from the limb of the Earth: elsewhere, the CR showers are viewed off-axis where the emission is very similar to the “backward” direction emission, thus only low-energy γ-rays will be detected.

The CR primary intensities and spectra at the top of the atmosphere depend on position as well as variations in the solar cycle (the solar modulation). The location dependence is due to the geomagnetic field configuration and the effect of this is to provide an effective rigidity cutoff that is position dependent. In Fig. 3 we show the variation of geomagnetic cutoff with geographic coordinates over the Earth modeled using the Stoermer approximation with invariant coordinates obtained from the IGRF-11 [23] multipole expansion of the geomagnetic field:

\[
R_{\text{cut}}(\theta_M, \theta, \phi) = \frac{M \cos^4 \theta_M}{r^2} \times \left(1 + \sqrt{1 - \sin \theta \sin \phi \cos^3 \theta_M}\right)^{-2} \tag{1}
\]

where \(M\) is the magnetic dipole moment of the Earth, \(\theta_M\) is the latitude from the magnetic equator, \(\theta\) is the zenith angle, \(\phi\) is the azimuthal angle measured clockwise from the north magnetic pole, and \(r\) is the distance from the dipole center. A visualisation of the “allowed”, “forbidden”, and penumbral zones corresponding to Eq. 1 is shown in Fig. 1 of [24]. We use Eq. 1 with the geomagnetic field model, along with the so-called “force-field” approximation [25] to treat the solar modulation, to model the intensities and spectra for CR primaries:

\[
I_{CR}(E_{\text{kin}}, \Phi, R_{\text{cut}}) = I_0(E_{\text{kin}} + Ze\Phi)^{-\gamma} \times \frac{(E_{\text{kin}} + m)^2}{(E_{\text{kin}} + m + Ze\Phi)^2 - m^2} \times \frac{1}{1 + (R/R_{\text{cut}})^{-\rho}} \tag{2}
\]

where \(I_0\) is the primary normalisation, \(E_{\text{kin}}\) is the primary kinetic energy, \(Z\) and \(m\) are the charge and mass of the primary, \(\gamma\) is the index of the unmodified primary spectrum, \(\Phi\) is the heliospheric modulation potential, \(R_{\text{cut}}\) is the location and direction dependent rigidity cutoff, and \(\rho\) is a fit parameter to smoothly describe the cutoff steepness. Figure 4 shows an example of the CR primary intensity > 1 GeV calculated using Eq. 2 at geographic coordinates (longitude, latitude) = (0°, 0°) for \(\Phi = 0\) MV (i.e., no solar modulation).

Using the above components, the atmospheric γ-ray emissivity can be calculated for monthly intervals as a function of geographic coordinates. Intervals of a month are the lowest time granularity of the models involved in the calculation (the variation of the geomagnetic field). The emissivity can then be integrated along the line-of-sight through the atmosphere, as shown in Fig. 1, to obtain the intensity for an orbiting satellite, like the Fermi–LAT. We will present a detailed comparison between our model and the available data from 511 keV to the multi-hundred GeV energies accessible by the Fermi–LAT at the conference.

References