PROCEEDINGS OF SCIENCE

Modeling of secondary cosmic ray spectra for 23 and 24 Solar Cycles

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The SecondaryCR model evaluates secondary particles spectra of electrons, positrons, muons, gammas, protons, neutrons, etc. in the Earth's atmosphere at different positions, altitudes and times during the 23rd and 24th solar cycles. We combine the model of secondary cosmic rays production in the Earth's atmosphere from existing models evaluating particles transport in heliosphere and magnetosphere and Corsika model [1] for interaction of primary cosmic rays with the atmosphere. For evaluation of spectra at 1AU on magnetopause we use mainly the results of HelMod model [2]. Transparency of magnetosphere was obtained by GeoMag model [3]. The evaluation of muon fluxes and spectra on the ground over the globe during 23nd and 24rd solar cycle were simulated. Comparison between hadronic models used in Corsika and comparison with BESS data were performed.

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†A footnote may follow.

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1. Introduction

The secondary cosmic rays production in the Earth's atmosphere depends on the position at globe, altitude and varies in time due to primary cosmic rays (PCR) spectra variation. The model with aim to describe spectra of secondary cosmic rays (SCR) should take into account the PCR intensities variation at the top of the atmosphere. To evaluate a PCR spectra entering atmosphere two another complementary models are needed. First one is the model describing a transport of particles through the heliosphere. The second model has to evaluate a transmissivity of magnetosphere for PCR.

Galactic cosmic rays from interstellar space, where they have constant in time spectrum called Local interstellar spectrum (LIS), pass through heliosphere and part of them reach the inner heliosphere. Due to the solar cycle the modulation process in heliosphere depends on time. The spectrum evolution in inner heliosphere close to the Earth orbit at 1AU is continously measured with high precision by PAMELA (since june 2006) [4] and AMS-02 experiments (since may 2011) [5]. In previous years the cosmic rays spectrum was measured with high precision and in wide range of energies during short time periods by balloon borne experiments BESS [6], [7] and CAPRICE [8] and on low Earth orbit by experiment AMS-01 [9]. The models of cosmic rays propagation in the heliosphere were extensively developed in the last almost 60 years [10]. To know an evolution of PCR in inner helioshere at 1AU distance from the Sun a model able to evaluate spectra for long period with high precision is needed. We have choosen to use a HelMod model [2] because of good agreement of his results with the measurements during 22 and 23 solar cycles. The proton spectra for this period are avialable in HelMod public catalogue at www.helmod.org. Those are PCR spectra at Earth planetary orbit outside of magnetosphere. PCR from interplanetary space registered at the top of atmosphere first enter and pass the Earth's magnetosphere. The second model evaluate trajectories of PCR in magnetosphere to find PCR spectra entrering the atmosphere where they produce SCR at different locations around the globe. We use a GeoMag96 model [3], [11] to evaluate transparency of magnetosphere.

2. Method

In this article we focus on secondary muon spectra in the Earth's atmosphere and their variation in time. We evaluate the spectra for net of points covering all globe and set of selected altitudes for two limit situations. For the solar minimum where highest intensities of SCR can be expected and for the solar maximum when smaller number of SCR is expected. We developed the Secondary Cosmic Ray (SecondaryCR) production model merging the results and simulations from HelMod model, GeoMag model and Corsika model package. To verify the SecondaryCR model validity we compared results from simulations with spectra measured by balloon borne experiment BESS at the Earth's surface. BESS muon spectra [12] were measured at Lynn Lake position with geographical latitude 56.50° and longitude 259.00° at 12:00 UTC 22.8. 1997. Corrected geomagnetic coordinates of Lynn Lake position for year 1997 were latitude 66.18° N and longitude 101.00° W. The altitude of Lynn Lake position is 300 m a.s.l.. The SCR are created mostly by proton and helium components of PCR. Transparency of the magnetosphere for protons and helium was evaluated in GeoMag96 model for 576 uniformly distributed incoming directions at Lynn Lake position

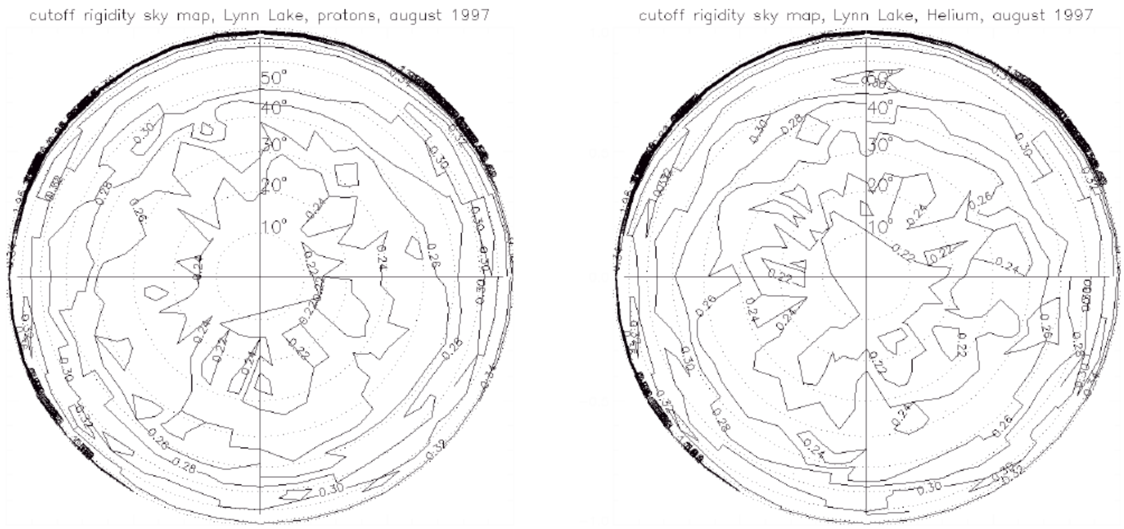

Figure 1: Sky map of effective cutoff rigidity in GV. Dotted circles show a 10° zenith angles.

for rigidities from 0.01GV till 200GV. For the rigidities higher then 200 GV is the magnetosphere transparent in all directions at all Earth's surface. The cutoff rigidities at Lynn Lake position for all sky directions are simmilar and low, with values close to 0.2 - 0.3 GV. As can be seen from the Figure 1, Lynn Lake position has negligible east-west asymmetry. Consequently there is almost no east-west asymmetry in PCR intensities from different directions. Due to high geomagnetic latitude the transmission function [3] of the magnetosphere for all energies is close to one, for both protons and helium. This made Lynn Lake position convenient for the basic verification of SecondaryCR model validity, because magnetospheric effect is small. In fact, due to low effective cutoff the situation at Lynn Lake at the top of the atmosphere is almost isotropic.

Previously [2] we do not use HelMod catalogue and GeoMag96 models to evaluate proton and helium spectra and level of isotropy at the top of atmosphere. We use published AMS-01 protons and helium spectra, but these are evaluated from measurements in short time period (Space Shuttle STS-91 flight in june 1998) and published for 10 geomagnetic regions [3]. Due to precision of AMS spectra they were appropriate for evaluation of SCR distribution at different positions and altitudes in atmosphere during the time of AMS-01 flight. But because AMS-01 spectra are measured at low Earth's orbit and do not describe east-west asymmetry, respectivelly it do not describe an anisotropy of the incoming cosmic rays, in this article we applied more precise approach taking into account all these influences. We use protons interplanetary spectrum at 1AU from HelMod model catalogue for august 1997 presented at Figure 2 as red solid line to reconstruct BESS results. After convolution by magnetosphere transmission function the spectrum at the top of atmosphere over Lynn Lake position was evaluated. On Figure 2 is the spectrum of protons entering the atmosphere presented by triangles connected by red solid line. We use an AMS-01 helium spectrum [13] as He4 spectrum, becasuse AMS-01 was measured one year later in similar conditions. We neglect the role of He3 and heavier nuclei for creation of SCR in atmosphere. For the part of PCR spectra with energies higher than 200GeV we use power law spectra fitted from region between 100GeV and 200GeV.

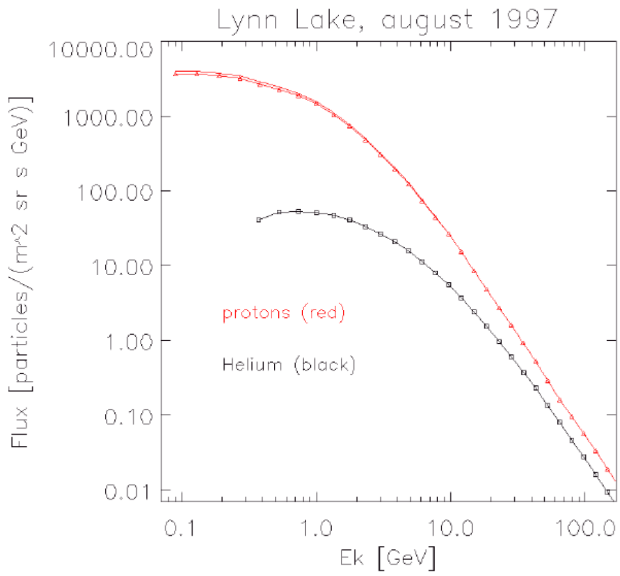

Figure 2: PCR differential intensity. Protons at 1 AU from HelMod model are presented by red solid line. Protons at the top of atmosphere are shown by red solid line with triangles. Spectrum of helium at the top of atmosphere is shown by black line with squares.

3. Comparison between hadronic models used in Corsika

The resulted proton and helium spectra at the border of atmosphere are used as inputs for Corsika simulations. As we already mentioned, particles at Lynn Lake position enter atmosphere almost isotropically. At the rigidities higher than 0.3 GV in the acceptance cone allowed by Corsika model, with maximum zenith angle 70°, they enter fully isotropically. PCR with rigidity below 0.3 GV (energy 47 MeV for proton) do not create any muons in range of energies measured by BESS experiment (0.6 to 20 GeV/c) at Lynn Lake altitude. We can therefore evaluate SCR production for Lynn Lake by isotropicaly injected particles in Corsika.

Corsika injects PCR isotropically to the cone with zenith angle range from 0° to 70° i.e. equal particle fluxes from all solid angle elements of the sky. We injected PCR with the set of logarithmically distributed energies. For the lower energies we inject more PCR, to avoid problems with low statistics. We inject particles in 62 energy bins from 90 MeV (140 thousands injected particles) till 98.8 TeV (1000 injected particles). We do not evaluate secondaries created by PCR with energies higher than 100 TeV, because they produce less than 0.1% of all muons registered at Lynn Lake position and altitude. The muon spectrum at altitude 300 m.a.s.l. was then evaluated in the way described in [14].

Simulations with identical input parameters have been performed for a set of high and low energy hadron interaction models combinations in Corsika package version 7.4 to evaluate production of SCR in the Earth's atmosphere. Thus we have tested a combinations of high energy hadron models. In Figure 3 we present comparison between muons spectra from protons PCR for different low energetic models GHEISHA, FLUKA, URQMD and BESS Lynn Lake measurements. Ratio between spectra in the figure show that GHEISHA is less similar to BESS muons spectrum in part

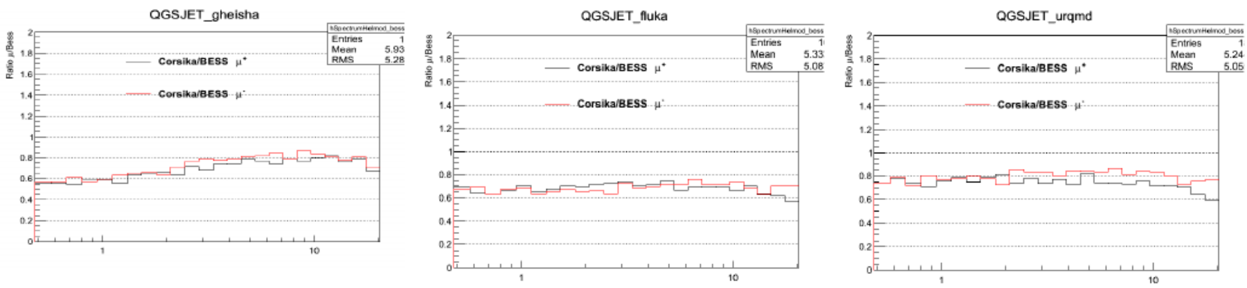

Figure 3: Comparison between muon spectra from protons PCR for different Corsika used low energy models GHEISHA, FLUKA, URQMD and BESS Lynn Lake measurements. Ratio between spectra show that GHEISHA is less similar to BESS muon spectrum in part below 3 GeV than FLUKA and URQMD. Shape of BESS muon spectra is most similar to URQMD results

Hadron interaction models	PCR Proton		PCR Helium	
High energy / Low energy	μ^-	μ^+	μ^-	μ^+
NEXUS / GHEISHA	14.20	17.50	3.22	3.30
QGSJET / GHEISHA	14.32	17.49	3.13	3.20
QGSJET / URQMD	16.01	19.03	3.36	3.45
QGSJETII / GHEISHA	14.52	17.83	3.21	3.27
QGSJETII / URQMD	16.29	19.34	3.41	3.48
VENUS / GHEISHA	14.28	17.71	3.22	3.29
VENUS / URQMD	15.95	19.20	3.35	3.45

Table 1: Total muons intensity at Lynn Lake in august 1997 position for different hadronic models in CORSIKA created by proton and helium PCR.

below 3 GeV than FLUKA and URQMD. The shape of BESS muon spectra is most similar to URQMD results.

Table 1 shows an integrals of muon spectra from different combinations of high and low energy hadron interaction models evaluated for all muon energies created by proton and helium PCR. Integrals are evaluated for half sphere acceptance at observation level. One can see two following general characteristics from Table 1. URQMD model produces more muons than GHEISHA close to the Earth's surface. It is approximatelly 10% for muons created by primary protons and approximatelly 6% for muons created by primary helium nuclei. Differences in muon production between high energy interaction models are in one order of magnitude smaller than between low energy models.

4. Comparison SecondaryCR results with BESS measurements

BESS vertical muons spectra at Lynn Lake position [12] were evaluated from muons incoming in acceptance cone with maximum zenith angle θ limited by condition $cos(\theta) > 0.9$. We select muons from simulation results in the same acceptance cone. The comparison of positive and negative muon spectra from model (for QGSJETII and URQMD hadronic models) with BESS Lynn

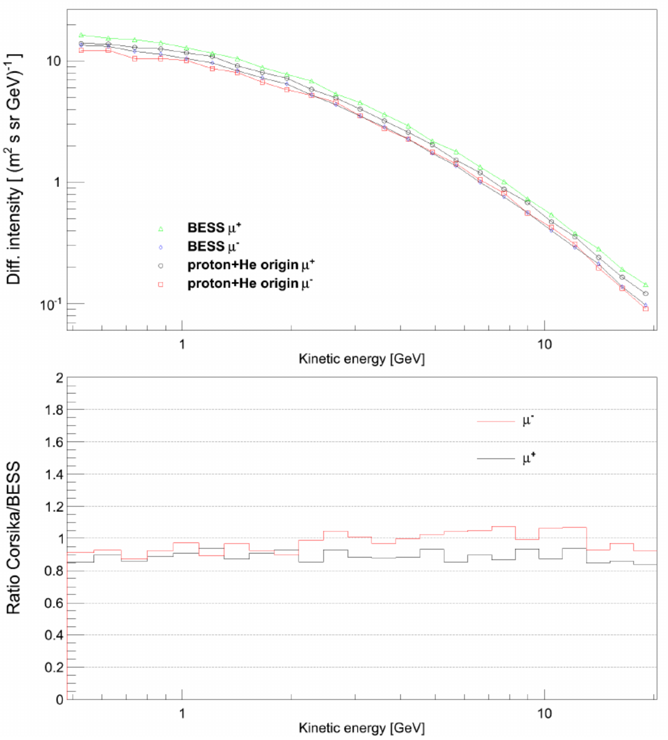

Figure 4: Simulated vertical spectra for combination of QGSJETII and URQMD hadronic models compared with BESS measured Lynn Lake vertical spectra (upper panel). Ratios of vertical muon spectra from SeconaryCR model and BESS measurements (bottom panel)

Lake spectra is presented in Figure 4. BESS vertical spectra for positive (green color on figure) and negative (blue color) muons are showed together with simulated positive (black) and negative (red) muon spectra from protons and He primaries. While simulated positive muons have slightly lower intensities than BESS muons over all energy range of spectrum, negative muons have lower intensities for energies under 2GeV and higher intensities for energies above 2GeV till 10GeV. Generally both positive and negative muons spectra from simulations show good agreement with BESS measurements.

From the comparison of the BESS measured vertical muon spectrum at Lynn Lake with SecondaryCR model's muon spectra evaluated for different combinations of high and low energy hadron interaction models we selected QGSJETII and URQMD combination as one which gives most simmilar results to measurements. Hence in the next simulations in SecondaryCR model we use QGSJETII and URQMD combination to evaluate muon spectra. Approximately 16% of all muons at Lynn Lake position is created by helium primaries. Figure 5 shows simulated positive and negative muons spectra for QGSJETII / URQMD hadronic interaction models created separately by primary protons and primary helium (upper panel of figure). The ratios in Figure 5 represent a number of muons created by protons as function of energy and same dependency for muons created by helium primaries.

The intensity of muon flux depends on incident angle. Generally, flux decreaseswith increasing zenith angle. For detector with increasingly expanding acceptance the muons differential intensities

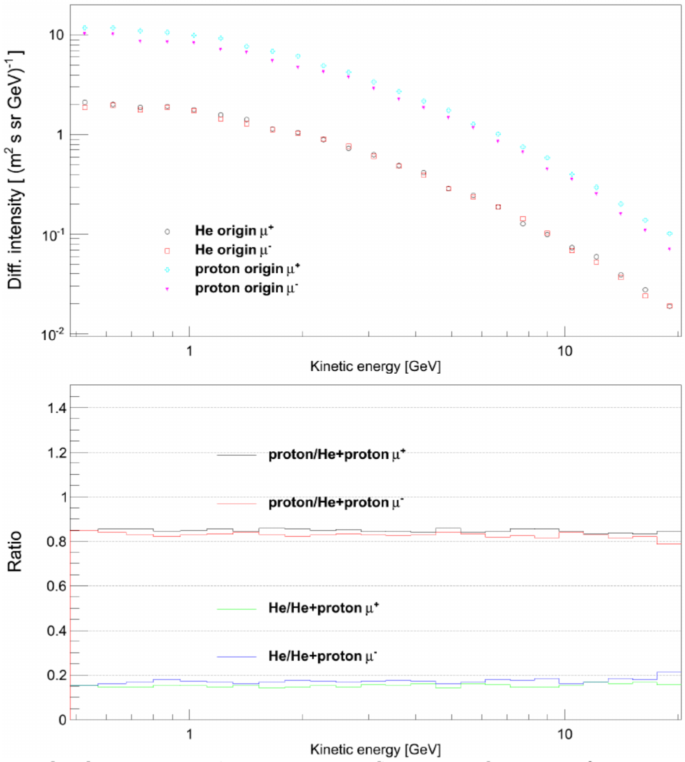

Figure 5: Simulated muon spectra (QGSJETII/URQMD) at Lynn Lake position from proton versus helium primaries (upper panel). Ratios of muons from protons to total number of muons at Lynn Lake as function of energy, together with ratio from by helium created to total number of muons.

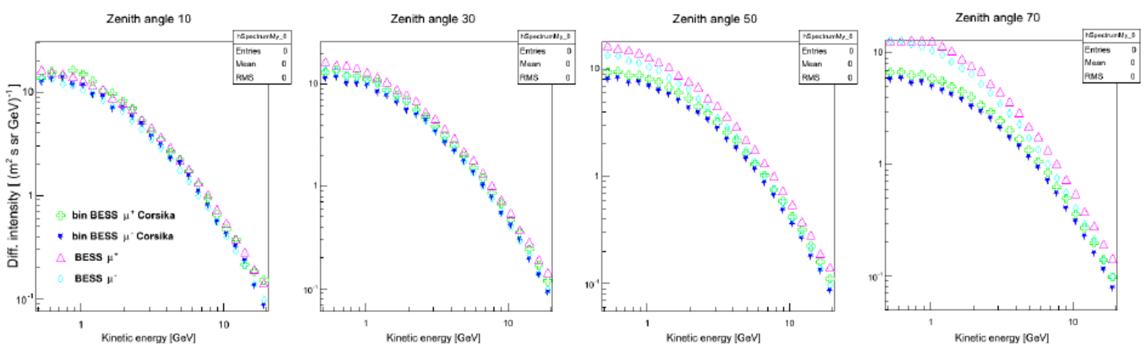

Figure 6: Differential muon spectra for a set of acceptances with 10° step in maximum zenith angles compared with measured vertical muon flux from BESS experiment.

decrease. Situation for Lynn Lake position for detectors with expanding maximum zenith angles is presented on Figure 6. Differential muon spectra at figure for a set of acceptances with 70° step in maximum zenith angles are compared with measured vertical moun flux from BESS experiment. The developed model is used for spectra evaluation from 23rd and 24th solar cycles. The results from this simulation will be published in next articles.

5. Conclusions

We combine model of secondary cosmic rays production in the Earth's atmosphere from existing models evaluating particles transport in heliosphere and magnetosphere and Corsika model for interaction of primary cosmic rays with the atmosphere. The comparison of muon spectrum evaluated by SCR model with BESS measurement in year 1999 is presented. SCR model results in the form of catalog will be published at secondaryCR.org.

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