Recent CORSIKA code simulations for space climate and astrophysics toward to Sun-Earth influences studies

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The capacity of CORSIKA code to simulate atmospheric cascade processes is demonstrated. The lateral distributions of atmospheric Cherenkov light flux for proton primaries are obtained. The application of these results is shown

The energy release of secondary cosmic rays, namely electromagnetic, muon, hadron and muon component is obtained for various primary particles and for different energies. Several applications are shown and the scientific potential is widely discussed.

Introduction

The field of cosmic ray (CR), which is part of astroparticle physics is connected with particle physics and astrophysics and also with space studies. This new and interesting field is rapidly extending during the last years after the discovery and observation of phenomena such as supernova remnants, active galactic nuclei, gamma ray bursts, which have significant impact to our knowledge of the universe.

At the same time there are still several very important unsolved problems connected with the origin and acceleration mechanisms of primary cosmic ray flux. Basically the origin of primary cosmic ray is a central unresolved problem in astroparticle physics. In addition the cosmic ray studies are complementary to gamma ray astrophysics since many gamma rays are produced in processes connected with cosmic ray such as synchrotron emission as example.

The measurements of the individual cosmic ray spectrum and the precise estimation of mass composition are very important in attempt to obtain more detailed information about the sources of primary cosmic ray and to build an adequate model of cosmic ray origin and acceleration mechanisms.

Another interesting problem is the existence of the “knee” i.e. the observed change of the slope of the primary cosmic ray spectrum. One possible explanation is based on the super nova remnants diffuse shock acceleration mechanism. Generally in this model the galactic supernovae are the only galactic candidate with sufficient energy. A possible issue within this model is that the supernova diffuse shock acceleration mechanism can produce high energy particles up to some maximal energy, which is limited by the lifetime of the shockwave.

Other possibility is in the case when the particles are so energetic and as a consequence they can no longer be confined in the acceleration region. According the model estimates the maximal energy reachable via this mechanism is about some 10^{14} eV. Obviously one observes particles with energy at least five orders of magnitude beyond this limit.

The problems connected with the existence of the “knee” of the spectrum are very important. In one hand the “knee” energies are easy explained by the limit of the mentioned above acceleration mechanisms by supernova remnants and it is the most evident point to support this model.

Above 10^{14} eV the only possibility for cosmic ray detection and measurement is ground based i.e. the detection of one or several of the components of secondary cosmic ray. One of the most convenient techniques in cosmic ray investigation is the atmospheric Cherenkov technique i.e. the detection of the Cherenkov light in extensive air shower (EAS). The Cherenkov light generated in EAS was observed first by Galbraith and Jelly in 1953 [1].

The Whiplle telescope used the technique of imaging the air shower to detect the Crab Nebula. This technique was proposed by Weeks and it is based of an array of photomultipliers at the focal plane of the telescope. The Cherenkov camera with good pixilation permits to discriminate the hadronic and electromagnetic showers and moreover to follow the development of the cascade into the atmosphere.

The capacities of imaging technique are widely discussed in [2]. The recently put in operation telescopes MAGIC and HESS reported significant results.

The detection of the air Cherenkov light at ground level using an array of telescopes or photomultipliers contrary to the image technique is also a powerful tool for the both of the mentioned above problems - gamma astronomy [3, 4] and the all particle energy spectrum [5].

The new telescopes in development need an accurate and detailed analysis of their performances i.e. the calculation of the detector response. In this connection building a databank of simulated events will permit to elaborate reconstruction method or to improve an existing one.

At the same time cosmic ray play an important role is space physics and new and modern field of space climate. Presently the effect of cosmic rays on climate changes is widely discussed. In several studies is suggested that CRs, namely their variations are factor leading to climate changes trough large diversity of mechanisms [6-9]. Obviously the Sun is the main climate driver. However CRs can play significant role, because the measured solar irradiance variability is small to explain the observed climate variations.

The solar variability is connected with indirect mechanism via CR to climate change such as atmospheric ionization. The CR induced ionization is the main ionization source in low and middle atmosphere and is related to cloud formation [10,11] trough cosmic ray-aerosol-cloud interactions [12,13].

In this connection the detailed and precise simulation of primary cosmic ray interaction with Earth atmosphere is very important.

CORSIKA code simulations

It exist large diversity of simulation tools, which permit modeling of cascade processes in different media including Earth atmosphere. Among several codes on the market the CORSIKA code [14] has become practically the standard in cosmic ray community.

This is a Monte Carlo program for detailed study of extensive air shower EAS evolution and properties in the atmosphere. The code simulates the interactions and decays of nuclei, hadrons, muons electrons and photons in the atmosphere up to energies of several 10^{20} eV. The output of the code gives information about the type, energy, direction, location and arrival time of the produced secondary particles at the selected observation level. In addition it is possible to obtain the energy deposit by different shower components and particles at given observation levels and to follow longitudinal shower development.

Lateral distribution of atmospheric Cherenkov light

For the aims of HECRE experiment proposal [15] a CORSIKA code [14] version 6.5 has been used for simulation of the development of EAS. The FLUKA 2006 [16] and QGSJET II [17] hadronic interaction models have been assumed respectively for low and high energy hadronic interactions.

The observation level was of 5500 m a.s.l. (536g/cm^2) which is near to the shower maximum. As a result the fluctuations in the shower development are not so important comparing to lower observation levels and it is possible to obtain flatter distributions of the different shower components.

The simulated particles are primary Proton, Iron, Helium, Oxygen, Carbon, Nitrogen, Silicon and Calcium nuclei and the lateral distribution of atmospheric Cherenkov light flux is obtained.

The majority of the Cherenkov photons are produced near to the shower maximum [18] in the energy range around the "knee".

The results for primary proton nuclei are presented in Fig. 1 and Fig. 2 for 10^{11}-10^{13} eV and 10^{13}-10^{17} eV respectively. In Y axis is shown the Cherenkov light density Q(R) measured in photons per m^2 and the corresponding standard deviation of the obtained Cherenkov light flux (the error bars). In X axis is shown the core distance in meters.

During the simulations the impact of atmospheric conditions [19] on generation and propagation of Cherenkov radiation is taken into account.

The lateral distribution of Cherenkov light flux in EAS produced by primary hadrons in the energy range 10^{13}–10^{16} is presented in Fig.3.

The observed difference is significant near to the shower axis and in the low energy region i.e. around energies of some 10^{14} eV. At the end of the distribution the difference is smaller.

However the significant differences observed in the fluctuations are well seen, especially the gradient of the distribution.

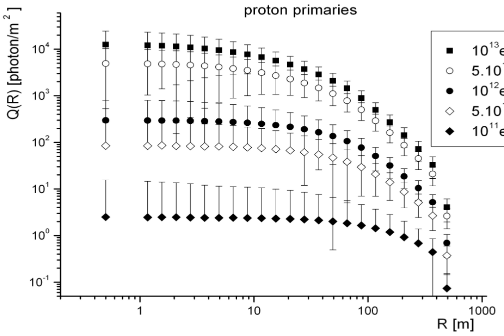

Fig.1. Lateral distribution of Cherenkov light flux in EAS produced by primary protons in the energy range 10^{11} –10^{13} eV at 536g/cm^2 observation level

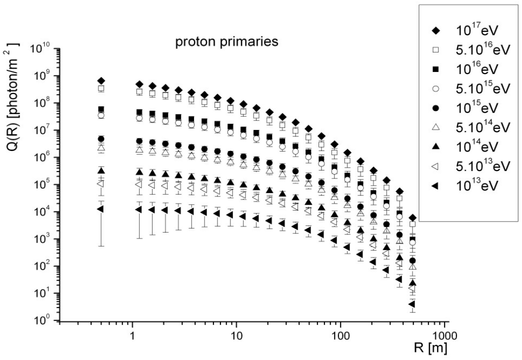

Fig.2. Lateral distribution of Cherenkov light flux in EAS produced by primary protons in the energy range 10^{13} –10^{17} eV at 536g/cm^2 observation level

Obviously in the energy range below the "knee" the obtained lateral distributions of Cherenkov light flux in EAS initiated by primary nuclei is between the Cherenkov light flux generated by proton and iron nuclei as incoming showers.

Generally the shape of the distributions is very similar with differences of the density values and the slope. At the same time the relative fluctuations varies as a function of the energy of the initial primary and as well the type.

Similar simulations are carried out for gamma quanta incident particles with practically the same data sets in CORSIKA code.

The main difference comparing to the lower observation levels is that one can not observe a typical for lower observation levels hump i.e. the characteristic ring of Cherenkov photons which appears between 90 and 120 m from the shower axis in the case of gamma quanta induced showers. This is due essentially to the high mountain observation level and thus the not so important influence of the atmosphere layer to the refractive index.

Comparing the lateral distribution of Cherenkov light flux in EAS generated by primary protons and gamma quanta one can see that the lateral distribution produced by primary nuclei is wider and with larger density fluctuations as was expected.

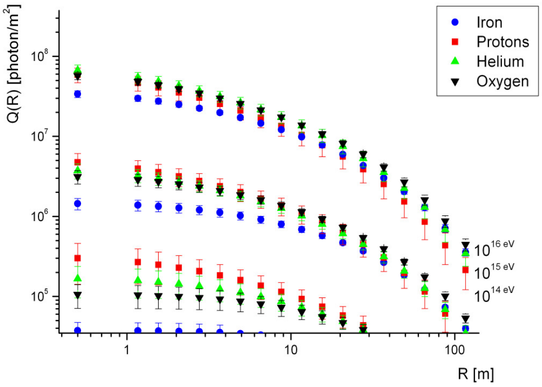

Fig.3. Lateral distributions of Cherenkov light flux in EAS produced by primary hadrons in the energy range 10^{13}–10^{16} eV at 536g/cm^2 observation level

The difference between lateral distributions of Cherenkov light flux in EAS initiated by proton and gamma showers in the energy range 10^{11}-10^{13} eV is presented in Fig. 4.

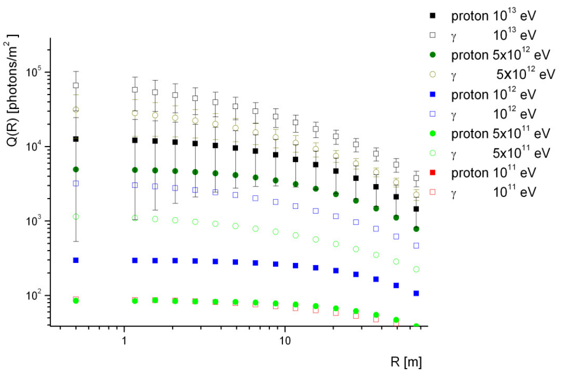

Fig.4.Difference between proton and gamma quanta produced Cherenkov light in EAS

Cosmic ray induced ionization

As was mentioned above energetic primary cosmic rays particles initiate nuclear-electromagnetic cascades in the atmosphere. The maximum in secondary particle intensity is observed at altitude of 15–26 km (Pfotzer maximum) and it depends on latitude and solar activity level [20]. Contrary to galactic cosmic rays only a small fraction of Solar energetic particles with energy around of several GeV produce cascades in the atmosphere, because their very steep energy spectrum.

In addition the geomagnetic field determines which particles arrive at the Earth at different latitudes. Each geomagnetic latitude is characterised by a cutoff rigidity R_c. Particles with less rigidity cannot arrive at this latitude.

The interest to cosmic rays as main ionizing source from 3–4 km up to about 50 km is rapidly growing since last decades. The ion pair production is related to many atmospheric processes, as example cloud formation and impact on the ozone layer.

Galactic CRs induce ionization in the stratosphere and troposphere and also in the independent ionosphere layer at altitudes 50-80 km in the D region [21]. This ionization is a result of the impact and energy deposit of secondary cosmic ray: electromagnetic, muon and hadronic components on the planetary atmosphere.

The estimation of CR induced ionization is possible on the basis of an analytical approximation of the atmospheric cascade [22] or on a Monte Carlo simulation [23]. A key issue, which allows to estimate the CR induced ionization for given location, altitude and spectrum of cosmic rays is based on use of ionization yield function Y defined according to the Oulu model [23].

$$Y(x,E) = \Delta E(x,E)\frac{1}{\Delta x}\cdot\frac{1}{E_{ion}}\cdot\Omega \qquad (1)$$

where ΔE is the deposited energy in atmospheric layer Δx in the atmosphere and Ω is a geometry factor, integration over the solid angle, E_{ion}=35 eV is the energy necessary for production of one ion pair [21, 24].

One can see that the the unit of ionization yield function is [sr.cm^2 g^{-1}]. Afterwards the ion pair production q by cosmic rays following given steep spectrum is easy calculated according the formula:

$$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(h,E)\cdot\rho(h)dE \qquad (2)$$

where $D(E,\lambda_m)$ is the differential primary CR spectrum at given geomagnetic latitude λ_m, Y is the yield function, $\rho(h)$ is the atmospheric density (g.cm^{-3}), h is the atmospheric depth in g.cm^{-2}, E_0 is the initial energy of CR spectrum.

The atmospheric cascade processes are simulated with CORSIKA 6.52 code [14] with corresponding hadron interaction subroutines FLUKA 2006 [16] and QGSJET II [17].

The ionization yield function Y was obtained following Oulu model [23] and procedure [25, 26] for proton primary particles.

On the basis of these results we obtained the ionization rates for solar minimum and solar maximum for different regions [27] (Fig. 5 and Fig. 6). In addition the impact of atmospheric profiles and different hadron interaction models on ionization yield function was investigated [28, 29], as well the contribution of Helium and heavy nuclei [30, 31].

The improved Sofia model [32] permits to study different processes related to atmospheric physics and chemistry, space climate and space weather .

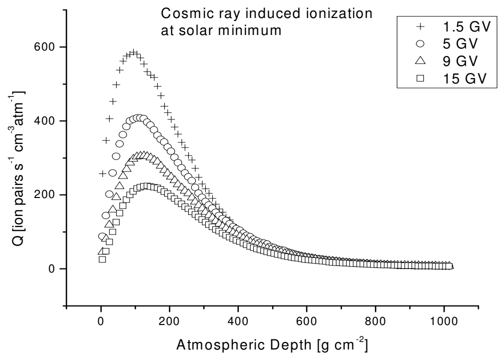

Fig.5. Ionization profiles for solar minimum for 1.5, 5, 9 and 15 GV rigidity

Discussion

Several recent studies demonstrate clear direct correlation between low cloud cover and CRs in few regions, which roughly corresponds to model predictions. Thus the obtained on the basis of CORSIKA code simulations improvement of Sofia model for cosmic ray induced ionization is very important. Moreover the lateral distribution of Cherenkov light in EAS in addition of astroparticle applications serve as a basis for development of a model for atmospheric transparency estimation.

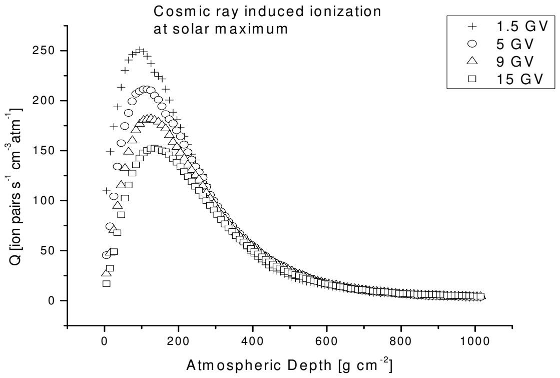

Fig.6. Ionization profiles for solar maximum for 1.5, 5, 9 and 15 GV rigidity

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