Comparison of simulated longitudinal profiles of hadronic air showers with MASS2 balloon data.

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Abstract

The KASKADE and CORSIKA air shower generators are compared to the data collected by MASS2 balloon experiment in 1991. The test of longitudinal profile for proton, helium and muon flux production provide good constraints on these air shower generators. KASKADE and CORSIKA especially with the new simulator UrQMD for low energies are found to fit these data well. This study is limited to a comparison of longitudinal profiles and therefore does not provide constraints on the overall shower development.

Key words: Atmospheric imaging Cherenkov technique, GeV-TeV energies, Atmospheric muons, Cosmic rays

1 Introduction

High energy gamma rays arriving at the earth interact early in the atmosphere to produce large electromagnetic air showers. The understanding of the shower development is of primary importance for the definition of future high energy cosmic ray experiments, as for example the HESS Cherenkov array, currently under construction in Namibia \cite{5}. In such an experiment, the Cherenkov light from the showers creates an image in the focal plane of a telescope. It allows an estimation of the energy, direction and impact parameter for gamma ray induced air showers, and permits cosmic ray rejection.

This technique is strongly correlated to our ability to predict, for incoming gamma rays of different energies, the amount of Cherenkov light generated as a function of altitude and their propagation to the observation level. Moreover, several sources of background have been identified. The main one comes
from the hadronic component of the cosmic rays. A hadron arriving in the atmosphere creates an hadronic shower in which muons and neutral pions are produced. Due to their initial energy, the muons radiate Cherenkov light along their full path and their life times are long enough for them to hit the ground. The neutral pions decay essentially into two photons and create an electromagnetic component in the hadron shower.

Even if a large part of these backgrounds can be identified using off-line analysis methods and if the muon signal does not survive the multi-telescope coincidence, the consequence of this background is an increased trigger rate for the experiment, inducing deadtime in the data acquisition. For this reason, the knowledge of the hadronic background is of primary importance. For this purpose, atmospheric shower generators have been developed over many years. The HESS collaboration currently uses KASCADE [1], CORSIKA [2], MOCCA [3] and the ALTAI program [4] developed at the Max-Planck Institute of Heidelberg. In this paper we focus on the two first generators and we take advantage of the data from MASS2 [6,7] balloon to test these hadronic shower generators. The comparison is made on the muon, proton and helium fluxes measured by MASS2 as a function of the altitude. Even if we do not check all processes in the hadronic shower development, the muon flux is directly correlated to the charged meson production and decay, mainly into pions and kaons, in the various processes involved in the hadronic interactions. The few measured values of proton and helium fluxes also constrain the interaction process of the primary particles and the production rate of secondary protons and helium nuclei generated by the heavy ion components of cosmic rays.

In the first three sections we describe the data taken by the MASS2 collaboration, the setup of the different generators tested in this paper and the analysis method. The next section is dedicated to the comparison and the systematical uncertainties. We then discuss these results and give our conclusions.

2 MASS2 experiment

The MASS2 balloon experiment was launched at Fort Sumner, New Mexico in September 1991. It was composed of a superconducting magnet spectrometer, a time of flight chamber, a Cherenkov detector and an imaging calorimeter. These devices permitted cosmic-ray muon, proton and helium identification and energy reconstruction for several atmospheric depths from 5 g.cm$^{-2}$ to 886 g.cm$^{-2}$ [6,7].

In this analysis we have used the following measurements: the momentum spectra of $\mu^-$ within different atmospheric depth ranges, $\mu^-$ and $\mu^+$ fluxes as a function of atmospheric depth respectively in the 0.3-40 GeV/$c$ and 0.3-
1.5 GeV/c momentum ranges, the proton and helium spectra at the top of atmosphere (5 g cm$^{-2}$) and their flux variation with atmospheric depth in the 4.1-14.1 GeV/c and 1.7-9.1 GeV/nucleon kinetic energy range respectively.

These data permit hadronic air-shower models to be tested. From proton and helium energy spectra measured at the top of atmosphere, we can simulate their hadronic interaction and air-shower development to compare the estimated muon, proton and helium fluxes with those measured at lower altitudes.

This study depends on the knowledge of geomagnetic field and a parametrization of atmosphere. The former was taken from the National Geophysical Data Center [17], we have used $B_x = 23.7 \mu T$ and $B_z = 45.5 \mu T$ for the Fort Sumner site. Concerning the latter, no specific measurement from this site was available. Several radiosonde observations were performed [16] in the vicinity, for example at Amarillo and Midland-Odessa (Texas) and Albuquerque (New Mexico). All results in this paper were obtained with the parametrization from Midland-Odessa data. The resulting uncertainties are discussed in section 6.

3 Analysis

Proton, helium, and heavier nuclei cosmic rays were injected at 5 g/cm$^2$ in the air-shower simulation programs. Proton and helium spectra were fitted from MASS2 data in the 4-100 GeV/c momentum range and 1.6-50 GeV/nucleon respectively. We took into account the low energy curvature and assumed a power-law limit at higher energies with a slope of $-2.7$ for protons and $-2.65$ for helium ([19]) up to 50 TeV/c. The heavier nuclei were generated using abundances from the Particle Data Group [18] and power-law spectra with slope -2.70. A sample of 10,000 showers per hadronic model were simulated.

Since muons suffer sizable multi-scattering, we generated primary particles isotropically from 0° up to 60° zenith angle, but only those secondary muons with angles up to 30° were used for the flux calculations. The fluxes at zenith were then derived from the integrated flux in this interval assuming a $\cos^{2.02}(\theta)$ angular dependance for muons [20].

In the following, all fluxes were normalized to the proton and helium fluxes at 5 g/cm$^2$. 

3
4 Generators setup

KASCADE [1] hadronic interactions are based on a model from Gaisser and Stanev. The momentum of a leading particle is computed along with the multiplicity and momenta of resulting pions. The model parameters are based on hadron-nucleus and π−nucleus collision data. This generator is used by atmospheric Cerenkov detectors such as CAT [21] and CELESTE [22]. CORSIKA is extensively used in high energy cosmic ray experiments and also by Cerenkov detectors as HEGRA [23]. CORSIKA allows several hadronic models. In version 5.60, ISOBAR and GHEISHA [8], were proposed for low-energy interactions (E_{lab} < 80 GeV for GHEISHA and 50 GeV for ISOBAR) and five other models for higher energies VENUS [15], QGSJET [13], DPMJET [10], SIBYLL [14] and HDPM [11]. CORSIKA has recently been upgraded to provide modified versions of hadronic packages and new ones, UrQMD [9] and NEXUS [12] respectively for low and high energy interactions.

5 Results

All available hadronic models are tested. We compute a $\chi^2$ which is the quadratic sum of the differences between the MASS2 [6,7] fluxes and the predictions of the simulations divided by an error term which is the quadratic sum of MASS2 error and the simulation statistical uncertainty. The MASS2 data points used in this $\chi^2$ are the fluxes measured at several atmospheric depths for a given energy range. Those points are shown figure 1 for proton and helium and figure 3 for muons. In the latter, five energy ranges are considered. The $\chi^2$ values obtained for all models are listed table 1.

5.1 Protons and Heliums

All models are in good agreement with the variation of the proton flux as a function of atmospheric depth as measured by MASS2. The best agreement is obtained with KASCADE and CORSIKA 6.00 with UrQMD, shown in figure 1. For the helium flux, the results are also satisfactory except for CORSIKA version 5.60 running GHEISHA. With this model, we observe a quantitative discrepancy with experimental data as the helium flux hardly decreases with atmospheric depth. This gives rise to huge $\chi^2$ values in table 1 for this model. This effect is corrected in version 6.00. KASCADE and CORSIKA 6.00 with UrQMD helium fluxes are also shown figure 1.
5.2 Muons

The $\mu^-$ spectra for different atmospheric depth ranges are estimated. Figure 2 shows the MASS2 observed spectrum in the atmospheric depth between 164 and 255 g.cm\(^{-2}\) along with the prediction of some models. The slope obtained with CORSIKA with GHEISHA is slightly steeper than the experimental one. KASCADE and CORSIKA 6.00 with UrQMD fit well the observed spectra.

When comparing the muon flux as a function of atmospheric depth for different energy ranges, the discrepancies appear more clearly. In figure 3 one can see that GHEISHA in CORSIKA 5.60 does not give enough muons at high momenta (above 4 GeV/c). On the same figure, we see that KASCADE and CORSIKA 6.00 with UrQMD are in good agreement.

5.3 Summary

It turns out that KASCADE hadronic model gives good estimations of the proton, helium and muon fluxes and spectra at various atmospheric depths. Concerning CORSIKA, results vary from one hadronic model to another. Though in this analysis we do not intend to test the high-energy interaction models, we can give some conclusions concerning the low-energy ones. ISOBAR is ruled out (it is not included in version 6.00), GHEISHA gives rise to too many low-energy muons (steeper spectrum) especially in version 6.00, and the model which best fits the data is UrQMD.

6 Uncertainties

The first uncertainty of the simulation is the cosmic rays spectrum slope which is about \(-2.7 \pm 0.06\) for nuclei. We have performed the same study with the energy spectrum slope varying within the range of its uncertainties. The differences obtained are found to be smaller than the statistical errors of the simulation. They are about 3\% for protons and 10\% for helium at about 50 g.cm\(^{-2}\), and 5\% for $p_\mu < 0.9$ GeV/c and 10\% for $p_\mu > 4$ GeV/c at about 100 g.cm\(^{-2}\) for muons. Hence, since MASS2 errors are of the same order, an upper limit of the variation of the $\chi^2$ value per degree of freedom with the primary spectrum slope is 0.5 which does not modify the conclusions concerning the low energy hadronic models.

Another uncertainty comes from the normalization of the muon flux with respect to the proton flux in MASS2. It is due to the event selection criteria
in their analysis which are not the same for protons and muons. This was checked [6] and this uncertainty on the ratio of selection efficiency between proton and muons does not exceed 2%.

In all the simulations performed in this study, an homogeneous magnetic field is assumed between the injection altitude and the ground whereas the actual geomagnetic field decreases with altitude within a 2.5% range. This approximation largely dominates the uncertainty on the magnetic field value on ground used in the models.

Another source of error may come for our atmospheric depth profile parametrization. On the one hand the data from the US Radiosonde database [16] are a mixture of measurements and models, and there is no data available for the Fort Sumner location and on the other hand the simulation codes require a parametrization of these data (several layers with $\rho(h) = a_i \times e^{-h/b_i}$). In order to quantify the impact of these uncertainties, we have performed the same simulation with two sets of atmospheric profile parametrization (fitted from Midland-Odesssa and Albequerque data). The discrepancy between the global $\chi^2$ obtained is about 1% but it does not affect the conclusions of this analysis.
Fig. 2. $\mu^-$ momentum spectra measured by MASS2 [6] (stars) in the atmospheric depth interval 164 and 255 g.cm$^{-2}$ compared with simulations.

7 Conclusion

Thanks to MASS2 balloon flight cosmic-ray measurements, a constrained test of the low-energy hadronic models of air-shower simulations is possible.

We have compared KASCADE and CORSIKA simulations with data. KASCADE gives rise to a proton, helium and muon flux evolution over atmospheric depth in agreement with experimental data. In CORSIKA, GHEISHA gives a steeper muon spectrum whereas the agreement is satisfactory with UrQMD. However we would like to stress the fact that this analysis only tests the mean longitudinal development of air-showers and for instance does not provide information on the lateral spread of the shower.
Fig. 3. $\mu^-$ and $\mu^+$ fluxes as a function of atmospheric depth for different momentum intervals measured by MASS2 [6] (stars) compared with simulations. Some of the distributions have been scaled.

The conclusions of this analysis are confirmed by the new results from CAPRICE98, a similar balloon experiment launched during spring 1998 on the same site [24]. The results from BESS [25,26] could also be used to continue this study for example to test another atmospheric condition.

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References

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† see Fig. 1, ‡ see Fig. 3

Table 1

Global $\chi^2$ results per degree of freedom from comparison of hadronic models with MASS2 data [7] [6] concerning proton, helium (figure 1) and $\mu$ (figure 3) fluxes as a function of atmospheric depth.


[18] The Particle Data Group, Cosmic rays (2000)


