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Extensive air showers and the physics of high energy interactions

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Abstract

Extensive air showers are still the only source of information on primary cosmic-rays and their interactions at energies above PeV. However, this information is hidden inside the multiplicative character of the cascading process. Inspite of the great experimental and theoretical efforts the results of different studies are often ambiguous and even conflicting. These controversies can partly be referred to imperfections of our models of high energy particle interactions.

The first part of the paper is concerned with this problem. The author thinks that the present models should be corrected to give slightly deeper penetration of the cascade into the atmosphere. In this respect the modification suggested by the QGSJET-II model seems to be the step in the right direction. The Sibyll 2.1 model provides a similar penetrating properties. However, this modification is not enough and a small additional transfer of the energy from EAS hadrons to the electromagnetic component is needed too. As a possible candidate for such a process the inelastic charge exchange of pions is discussed.

In the second part of the paper the author discusses the need to account for the interaction of EAS with the stuff of detectors, their environment and the ground in the light of the 'neutron thunder' phenomenon, discovered recently.

Keywords: Cosmic-rays; Extensive air shower; Interaction model

1. Introduction

There is a big progress in the analysis of experimental data on extensive air showers (EAS) during the last two decades. However, one cannot say that we understand all the phenomena and characteristics of EAS which we observe. Partly this dissatisfaction is due to the controversies in experimental data themselves, partly due to still remaining imperfections of the analysis. We certainly need to improve our understanding of EAS.

This paper does not aim to give a comprehensive review of all high energy interaction models, event generators and EAS simulation codes. It consists of two different parts. In the first part I point out some problems related to the particle interaction models which so far pose questions at high energies. I do not go into the theoretical foundations of various interaction models, but stay within a pure phenomenological approach. Within it I indicate the possible way to improve the models. The theoretical basis of some recent models can be found in [1].

In the second part of the paper I shall touch the problems related to some effects of the EAS interaction with the environment.

2. High energy interactions

2.1. The consistency of the results

The EAS is a complex phenomenon – it has several different components: electromagnetic – electrons, positrons and gamma-quanta, muons and hadrons – nucleons, pions, kaons and so on. Besides that there are neutrinos which need massive detectors to be studied. Due to their small

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interaction cross-section they are detected not as multiple shower neutrinos, but as single ones. So far they are not combined with other EAS components in the analysis of experimental data, but they certainly play a role in the energy balance. Optical cherenkov and fluorescence photons emitted by charged shower particles are also used as a powerful tool for the study.

Since the characteristics of observed showers are the product of the primary cosmic-ray (CR) energy spectrum, mass composition and high energy interactions, the only way to disentangle them is to achieve the self-consistency in the derivation of the properties of primary CR from different observables and vice versa – the derivation of observed characteristics for different shower components and different observation levels from the same primary CR and the interaction model.

There were many efforts in the past to use models of the popular CKP or scaling type. With the development of the QGS model [2] it has been shown that this model gives a satisfactory description of both EAS [3,4] and single, unassociated CR components in the atmosphere [5–7]. However, those old studies used as a rule different cascading algorithms and programs, which certainly produced an additional uncertainty in the results and reduced the credibility of the conclusions. It is to the credit of the KASCADE people who spend great efforts to develop and to distribute freely the CORSIKA code [8]. With this code the analysis of experimental data can now be made at the level much better than before.

2.2. The improvement of models

An early analysis of models indicated that the best consistency for the mean logarithmic mass $\langle \ln A \rangle$ of primary CR derived from the $\frac{N_\mu}{N_e}$ ratio and from X_{max} can be achieved for the QGSJET model [9]. Here N_μ, N_e are muon and electron sizes of EAS, respectively and X_{max} – the depth of the shower maximum. Later a similar conclusion about the preference of QGSJET model has been made on the basis of the analysis of the EAS hadronic core [10]. After some improvements the SIBYLL model, version 2.1 joined the list of the best, most popular and often used models [11].

However, the closer look reveals that some inconsistencies still remain. It has to be said that indications of possible inconsistencies appeared more that 30 years ago when the mismatch between the direct and indirect measurements of the primary energy spectrum has been noticed: the indirect measurements based on the EAS model calculations gave as a rule the higher CR intensity in the PeV region than that derived by the extrapolation of direct measurements from the lower energies – the so called 'bump' problem [12]. More recently this mismatch has been confirmed by [13]. Among possible explanations there was an assumption that even the best models give an overestimation of the primary energy from the observations in the atmosphere. It could happen if the shower penetrates deeper into the atmosphere and has more charged particles at the observation level than it is expected from model calculations.

Observations of the EAS cherenkov light in the PeV region confirmed this deeper penetration [14]. As a consequence, the primary mass attributed to such showers derived from observed X_{max} values and N_μ/N_e ratio after the comparison with model calculations turned to be smaller than the true primary mass. There was a number of ideas how to increase the penetrability of the showers, for instance, introducing the higher cross-section for the charm production [15] or hypothetical strangelets [16,17], but those models are still in the stage of development. The possibility to improve the models were discussed also in [14,18]. In [14] it has been assumed that the cross-section and the inelasticity of the proton interactions in the air are in fact smaller than in the models, although they still agree with measurements at the lower end of the error bars. Their reduction allowed to improve the agreement between the predictions of the models and the results of the X_{max} measurements. There were some indications of the lower cross-sections in the past measurements of hadrons in the EAS cores [19]. The latest measurements of the inelastic cross-sections confirmed the slower rise of the interaction cross-section with energy [20,21]. Therefore, there are experimental indications that EAS may in fact penetrate deeper, than predicted by models.

There are also efforts to improve models not just on the pure phenomenological, but also on the theoretical basis. The idea that the density of partons at high energies becomes so high that they cannot interact independently of each other has been discussed long ago [22]. However, it is to the credit of Ostapchenko, who updated the QGSJET01 model including the non-linear effects of parton interactions, developed it to the status of the Monte Carlo event generator and together with his colleagues in Karlsruhe incorporated it into the Corsika code [23,24]. As a consequence of the non-linear effects, the interaction cross-section (at least for pions), the multiplicity of secondaries and the inelasticity of the collisions decreased slightly which helped atmospheric cascades to penetrate deeper. Apparently the reduction of the inelasticity plays the major role in the increased penetrability. Due to its smaller inelasticity the updated Sibyll 2.1 model also provides EAS with a greater penetrability than previous models. Certainly these improvements are the step in the right direction.

However, the only introduction of the non-linear effects of parton interactions seems to be not enough. This suspicion appears when the examination of the hadron component is included into the analysis. It has been shown in [25] that the primary mass composition derived mainly from hadron and muon components is heavier than that which can be obtained using mainly electromagnetic and muon components. Muons are usually less model dependent at the fixed primary energy, since they are penetrating particles and are collected from all atmospheric altitudes representing something like an integral over the longitudinal