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The KASCADE-Grande energy spectrum of cosmic rays and the role of hadronic interaction models

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Abstract

Previous results obtained by KASCADE-Grande using the QGSjetII-02 hadronic interaction model have shown that the energy spectrum of cosmic rays between 10^{16} eV and 10^{18} eV exhibits a significant hardening at approximately 2×10^{16} eV and a slight but statistically significant steepening close to 10^{17} eV. Moreover, the analysis with QGSjetII-02 suggests that the break observed around 10^{17} eV is caused by the heavy component of primary cosmic rays. In this paper, we report on the results of similar analyses performed using the SIBYLL 2.1 and EPOS 1.99 hadronic interaction models to interpret the data. The present results confirm qualitatively the previous findings. However, the intensity of the all-particle spectrum, the positions of the hardening and steepening of the spectrum, as well as the relative abundance of the heavy and light mass groups depend on the hadronic interaction model used to interpret the data.

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1. Introduction

Due to the rapidly falling intensity with increasing energy, cosmic rays of energies above 10^{15} eV can be studied only indirectly by observations of extensive air showers (EAS) which are produced by the interaction of cosmic particles with nuclei of the Earth's atmosphere. The all-particle spectrum has a power-like behavior ($\propto E^{\gamma}, \gamma \sim -2.7$) with features known as the 'knee' around 3-5 $\times 10^{15}$ eV and 'ankle' at 4-10 $\times 10^{18}$ eV, respectively, where the spectrum shows a steepening and hardening, respectively, of the spectral index by $|\Delta\gamma| \sim 0.3 - 0.4$. Many astrophysical models interpreting the origin of the knee assume the existence of various breaks which depend on the charge of primary nuclei (Peters, 1961; Hörandel, 2004). This seems to be in agreement with previous findings of EAS-TOP and KASCADE which have shown that the knee at 3-5 $\times 10^{15}$ eV is caused by the decrease in the flux of light mass primaries (Aglietta et al., 2004a,b; Antoni et al., 2005) and by recent findings of KASCADE-Grande (Apel et al., 2011) which indicate a bending of the heavy mass-group around 10^{17} eV. Moreover, KASCADE-Grande data indicate also the presence of a hardening of the spectrum around 2×10^{16} eV (Apel et al., 2012) that can be expected (De Donato and Medina-Tanco, 2009) if a gap exists between the breaks of the most abundant light and heavy primaries.

The energy range between 10^{17} eV and 10^{19} eV is also very interesting as it is the region where a transition from a galactic dominated to an extra-galactic dominated composition is firmly expected (Hillas, 2005; Berezinsky et al., 2007). The ankle might mark indeed such a transition. Therefore, the study of the chemical composition and of the shape of the energy spectrum in this energy range is also of great interest.

Despite the fact that ground-based observation of cosmic rays allows collecting large data samples, thereby, reducing statistical uncertainties, one has to rely on the results of simulations and the description of hadronic interactions for reconstructing the properties of the primary particles. Since the required energies and important kinematic regions of these interactions are beyond the range of collider or fixed target experiments, the interaction models used are uncertain and differ in predictions. Therefore, a cross-check of the results obtained with different interaction models will help in understanding the systematic effects of this kind.

In this paper, we present the results on the all-particle energy spectrum and mass-group separation of KASCADE-Grande data interpreted using the SIBYLL 2.1 (Engel et al., 1992), and EPOS 1.99 (Werner et al., 2006) high-energy hadronic interaction models in the CORSIKA framework (Heck et al., 1998), and compare them to the previous findings obtained using QGSjetII-02 (Ostapchenko, 2006). In this sense the present paper has to be considered as a follow-up of the analyses presented in Apel et al. (2011, 2012). This is the reason why the technique to infer the energy spectrum and mass separation is the same as in QGSjetII-02 analyses.

In the following, the names will be abbreviated as SIBYLL, EPOS and QGSjet, respectively. In all cases, FLUKA (Battistoni et al., 2007) is used to describe the low-energy interactions in the air-shower development.

2. The Technique

The technique employed to derive the all-particle energy spectrum and the abundance of 'light' and 'heavy' primaries is based on the correlation between the number of charged particles (N_{ch}) with energy E > 3 MeV, and muons (N_{μ}) with kinetic energy E > 230 MeV on an event-by-event basis. The method itself has been described in detail in Bertaina et al. (2011) where QGSjet simulated showers were used to analyse the data. Here, we summarize the main points and describe the results obtained using SIBYLL and EPOS.

A sample of Monte Carlo events was simulated including the full air shower development in the atmosphere, the response of the detector and its electronics as well as their uncertainties. In this way, the parameters reconstructed from the simulation are obtained in the same way as for real data. The EAS events are generated with an isotropic distribution with spectral index $\gamma = -2$, i.e. roughly one order of magnitude harder than the measured spectrum. Hence, the simulated showers are weighted to describe a softer energy spectrum with $\gamma = -3$. Sets of simulated events were produced in the energy range from 10^{15} to 10^{18} eV with high statistics and for five elements: H, He, C, Si and Fe, representative for different mass groups (≈257,000 events per primary for SIBYLL and EPOS, ≈353,000 in case of QGSjet). Some events up to $3 \cdot 10^{18}$ eV were also generated in order to cross-check the reconstruction behavior at the highest energies.

The relevant components of the KASCADE-Grande (Apel et al., 2010) multi-detector experiment used for the present analysis are the Grande and KASCADE arrays. Grande is formed by 37 stations of 10 m^2 scintillation detectors each, spread over an irregular grid with an average spacing of ~137 m, covering an area of about 700×700 m^2 (see Fig. 1) . The KASCADE array is composed of 252 detector stations (~3.2 m^2 each) on a square grid and with 13 m spacing spread over an area of