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Inconsistencies in EAS simulations - longitudinal vs. lateral development

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In present-day air shower experiments several techniques are used to determine shower properties, e.g. the electromagnetic, muonic, and hadronic components as well as the Cerenkov and fluorescence light are investigated. The all particle spectrum of cosmic rays and the mean logarithmic mass have been derived. Most all–particle energy spectra are compatible with extrapolations of the energy spectra of individual elements, measured directly at the top of the atmosphere. An investigation of the mean logarithmic mass derived from EAS observables yields systematic differences between experiments measuring the lateral EAS development on one side and experiments investigating the longitudinal EAS development on the other hand. The inconsistencies can be reconciled by reducing the logarithmic increase of the total inelastic hadronic cross sections as function of energy.

1. Introduction

Cosmic rays are explored using several experimental techniques. The energy spectra of individual elements have been directly measured above the atmosphere up to energies of several 10^{13} eV and for groups of elements up to 10^{15} eV. Due to the fast decreasing flux, measurements at higher energies require large detection areas or long exposure times, which presently can only be realized in ground–based detector systems. These experiments measure extensive air showers (EAS), generated by interactions of the high energetic cosmic rays with the nuclei in the atmosphere.

Most EAS experiments deduce from their measurements the all–particle energy spectrum and the mean logarithmic mass $\langle \ln A \rangle$. The compatibility of the various experimental results is investigated with respect to these two quantities. The energy spectra obtained by direct measurements are extrapolated to high energies using a model with rigidity dependent cut–offs for the individual element spectra, the *poly–gonato* model[1]. The all–particle spectrum and the mean logarithmic mass obtained are compared to results from EAS experiments.

2. The poly–gonato model

The model parametrizes the energy spectra of individual elements, assuming power laws and taking into account the solar modulation at low energies. Above about $Z\cdot 10$ GeV, the modulation due to the heliosphere is negligible and the energy spectra of cosmic–ray nuclei are assumed to be described by power laws. The following ansatz is adopted to describe the flux for particles with charge Z

$$\frac{d\Phi_Z}{dE_0}(E_0) = \Phi_Z^0 E_0^{\gamma_Z} \left[1 + \left(\frac{E_0}{\hat{E}_Z}\right)^{\epsilon_c}\right]^{\frac{\gamma_c - \gamma_Z}{\epsilon_c}} . \quad (1)$$

The absolute flux Φ_Z^0 and the spectral index γ_Z quantify the power law. The flux above the cut–off is modeled by a second and steeper power law. γ_c and ϵ_c characterize the change in the spectrum at the cut–off energy $\hat{E}_Z$. Both parameters are assumed to be identical for all spectra, γ_c being the hypothetical slope beyond the *knee* and ϵ_c describes the smoothness of the transition from the first to the second power law.

To study systematic effects, instead of a common spectral index for all elements above the cut–off, also a constant difference $\Delta\gamma$ between the spectral indices below and above the *knee* is tried and the spectrum for an element with charge Z is assumed as

$$\frac{d\Phi_Z}{dE_0}(E_0) = \Phi_Z^0 E_0^{\gamma_Z} \left[1 + \left(\frac{E_0}{\hat{E}_Z}\right)^{\epsilon_c}\right]^{\frac{-\Delta\gamma}{\epsilon_c}} . \quad (2)$$

Since the origin of the *knee* is still under discussion, three assumptions to parametrize the cut–

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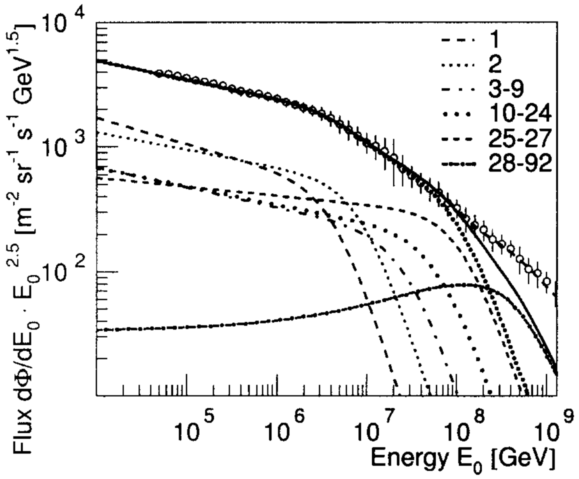

Figure 1. Average all-particle energy spectrum. The line through the data represents a fit of the sum spectrum for elements with $1 \leq Z \leq 92$ according to the *poly-gonato* model with rigidity dependent cut-off for common $\Delta\gamma$. The dotted line shows the spectrum for $1 \leq Z \leq 28$. In addition, energy spectra for groups of elements are shown. Above 10^8 GeV the dashed line reflects the average spectrum [1]. Below this energy the average measured spectrum (open circles) coincides with the sum of $1 \leq Z \leq 92$, the solid line.

off energy are scrutinized

$$\hat{E}_Z = \begin{cases} \hat{E}_p \cdot Z & \text{; rigidity dependent} \\ \hat{E}_p \cdot A & \text{; mass dependent} \\ \hat{E}_p & \text{; constant} \end{cases} \qquad (3)$$

Knowing the flux $d\Phi_Z/dE_0(E_0)$ for the species with charge Z, the flux of the all-particle spectrum is obtained by summation over all cosmic-ray elements

$$\frac{d\Phi}{dE_0}(E_0) = \sum_{Z=1}^{92} \frac{d\Phi_Z}{dE_0}(E_0) \quad . \qquad (4)$$

This equation contains the parameters Φ_Z^0 and γ_Z for each element and the common parameters, $\hat{E}_p$, ϵ_c, and γ_c or $\Delta\gamma$. Φ_Z^0 and γ_Z are obtained from direct measurements of individual nuclei. The remaining three parameters are derived from a fit to the all-particle spectrum as obtained by indirect measurements.

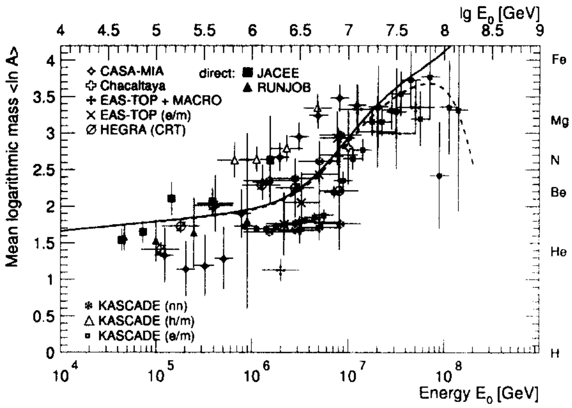

Figure 2. Mean logarithmic mass vs. primary energy from measurements of distributions for electrons, muons, and hadrons at ground level, see [1]. Predictions according to the *poly-gonato* model are represented by the solid line. The dashed line is obtained by introducing an *ad-hoc* component of protons only.

3. Energy spectra

The all-particle energy spectra from many EAS experiments have been compiled by the author [1]. Experimental observables utilized in the experiments include the number of electrons, muons, and hadrons measured at ground level as well as the observation of Čerenkov and fluorescence light. The detectors are located at atmospheric depths from 606 to 1022 g/cm^2. Despite of these differences the resulting all-particle spectra agree quite well. The experimental spectra have been normalized to the extrapolations of direct measurements by a proper renormalization of the individual energy scales always within the quoted errors. For experiments measuring in the knee region ($\approx$ 4 PeV) energy shifts of less than 12% are required, indicating the good agreement of the individual measurements. At energies above 10^8 GeV the maximum renormalization factor turns out to be 20%. Taking into account the uncertainties of the different models used in the simulations to interpret the observed data an absolute energy calibration better than 20% is a remarkable result.

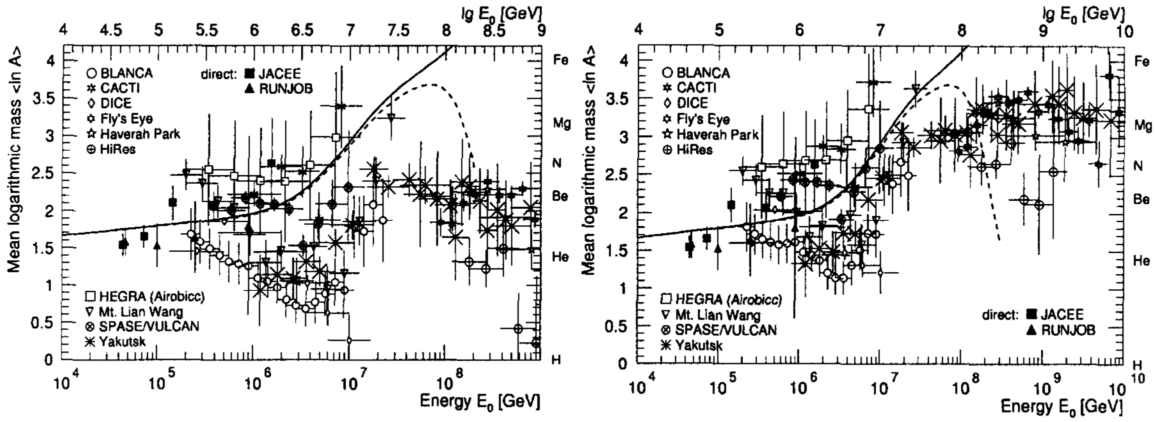

Figure 3. Mean logarithmic mass vs. primary energy, derived from the average depth of the shower maximum X_{max} using CORSIKA/QGSJET simulations. Left: using original QGSJET [1], right: using QGSJET with modified cross sections [3]. Predictions according to the *poly–gonato* model are represented by the solid line. The dashed lines are obtained by introducing an *ad–hoc* component of protons only.

The average all–particle spectrum, calculated from the normalized experimental results is shown in Fig. 1. The free parameters of the *poly–gonato* model have been obtained by fits to this spectrum. In the case of a rigidity dependent cut–off and a common $\Delta\gamma$, e.g. the knee of the proton component is found to be at $\hat{E}_p = 4.5 \pm 0.5$ PeV, and the values $\Delta\gamma = 2.10 \pm 0.24$ as well as $\epsilon_c = 1.90 \pm 0.19$ have been obtained.

4. Mean logarithmic mass

The mean logarithmic mass exhibits on a first glance a more confusing behaviour than the all–particle spectrum. A compilation of all experiments, unregarded their techniques used, yields a large scatter of $\langle \ln A \rangle$ [2]. At 10^7 GeV the $\langle \ln A \rangle$ values cover a range from 0 to 3.5, and no real conclusion can be derived concerning the mass composition above knee energies.

But, a closer look reveals systematic differences for the $\langle \ln A \rangle$ values obtained with different experimental techniques. Experiments exploring the lateral distribution of particles at ground level by measurements of electrons, muons, and hadrons obtain $\langle \ln A \rangle$ values as compiled in Fig.2, for references see [1]. The mean logarithmic mass calculated according to the *poly–gonato* model with rigidity dependent cut–off is given by the solid line. Since more and more elements reach their cut–off energy $\hat{E}_Z$, the mean logarithmic mass increases with rising energy and would finally reach pure uranium. However, above 100 PeV the sum spectrum for $1 \leq Z \leq 92$ is not sufficient to describe the all–particle spectrum. For this reason, a new component is introduced *ad hoc* in order to fill the difference between the sum spectrum and the all–particle spectrum. Anticipating a pure proton composition yields a lower limit for the $\langle \ln A \rangle$ values, indicated as dashed line in Fig. 2. The results of experiments investigating the lateral EAS development are well compatible with the extrapolations of the direct measurements as can be inferred from Fig. 2.

On the other hand are experiments which study the longitudinal shower development in the atmosphere, observing Čerenkov or fluorescence light. The obtained average depth of the shower maximum X_{max} has been compiled in [1]. X_{max} values have been simulated using CORSIKA/QGSJET for primary protons as well as iron nuclei and corresponding $\langle \ln A \rangle$ values have been calculated from the measured X_{max} values. The results are displayed in Fig.3 (left). They are not compatible with the *poly–gonato* model.

The differences can be explained by the longitudinal development of EAS, i.e. the results indicate that the measured showers penetrate deeper

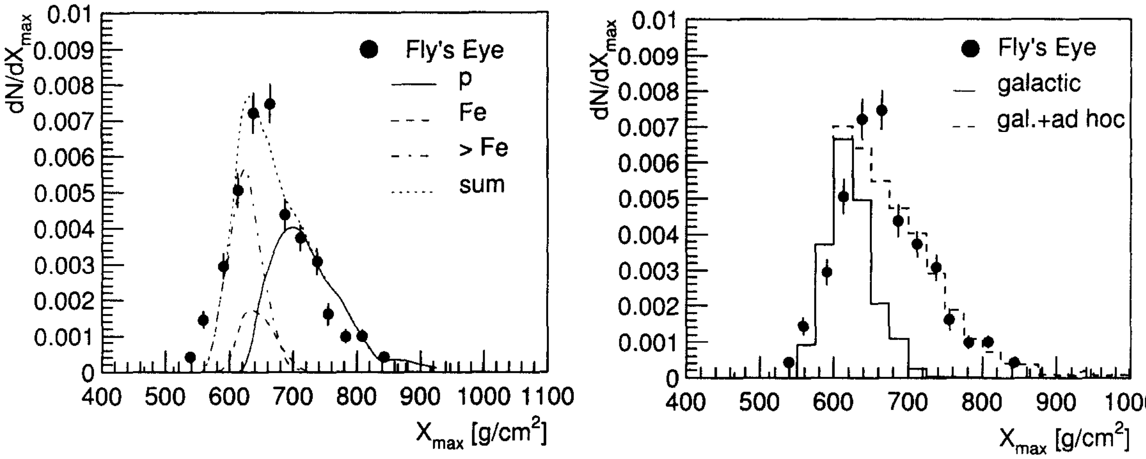

Figure 4. Distributions for the average depth of the shower maximum X_{max} for $5 \cdot 10^8$ GeV to 10^9 GeV. The measured values of the Fly's Eye experiment [4] are compared to simulated values using CORSIKA/QGSJET. Left: original QGSJET, X_{max} values shifted by $\Delta X_{max} = 30$ g/cm^2 [1]. Right: QGSJET with modified cross section [3].

into the atmosphere as predicted by QGSJET. This is confirmed by an investigation of the measured X_{max} values of the Fly's Eye experiment, presented in Fig. 4 (left). The simulated distributions had to be shifted by $\Delta X_{max} = 30$ g/cm^2 in order to obtain agreement with the experimental values.

Inspired by these observations, the total inelastic hadronic cross section has been modified in the model QGSJET and the influence on X_{max} has been studied [3]. It has been found, that a modest increase of the cross section to $\sigma_{pp}^{inel} = 64$ mb at 10^8 GeV describes the data best. The resulting X_{max} distributions are compared in Fig. 4 (right) to the Fly's Eye measurements. No artificial shift in X_{max} is necessary to obtain agreement.

Using the modified version of QGSJET, $\langle \ln A \rangle$ values as shown in Fig. 3 (right) are obtained. The results agree much better with the extrapolations of the direct measurements as compared to the original QGSJET values. The scattering of the experimental results investigating the longitudinal development around the line given by the *poly-gonato* model is now comparable to the deviations of the observations of the lateral EAS development, see Fig. 2.

5. Conclusion

An investigation of the mean logarithmic mass obtained by many EAS experiments reveals systematic differences between experiments exploring the lateral and longitudinal development of EAS. The measured showers seem to penetrate deeper into the atmosphere as predicted by the model QGSJET. Therefore, the increase of the total inelastic cross section has been reduced in the model. As consequence, the $\langle \ln A \rangle$ values obtained from X_{max} observations are compatible with experiments measuring the lateral EAS development and the results of most EAS experiments are compatible with the extrapolation of direct measurements according to the *poly-gonato* model.

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