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Results from the KASCADE, KASCADE-Grande, and LOPES experiments

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Abstract. The origin of high-energy cosmic rays in the energy range from 10^{14} to 10^{18} eV is explored with the KASCADE and KASCADE-Grande experiments. Radio signals from air showers are measured with the LOPES experiment. An overview on results is given.

1. Introduction

One of the most remarkable structures in the energy spectrum of cosmic rays is a change of the spectral index γ of the power law $dN/dE \propto E^\gamma$ at an energy of about 4 PeV, the so called *knee* [1, 2, 3]. The origin of the *knee* has not been resolved yet and a convincing explanation of the *knee* structure is thought to be a corner stone in understanding the origin of galactic cosmic rays. In the literature various reasons for the *knee* are discussed, being related to the acceleration and propagation processes of cosmic rays as well as to interactions in interstellar space or the Earth's atmosphere [4, 5].

The steeply falling energy spectrum requires large detection areas at high energies. The largest balloon-borne experiment with single-element resolution (TRACER, 5 $m^2\,sr$) reaches energies of a few 10^{14} eV [6]. To study higher energies, experiments covering several 10^4 m^2 and exposure times exceeding several years are necessary, which, at present, can only be realized in ground-based installations. They measure the secondary products generated by high-energy cosmic-ray particles in the atmosphere – the extensive air showers. The challenge of these investigations is to reveal the properties of the shower inducing primary particle behind an absorber – the atmosphere – with a total thickness at sea level corresponding to 11 hadronic interaction lengths or 30 radiation lengths.

One of the most advanced experiments in the energy range from 10^{13} eV to 10^{17} eV is the experiment KASCADE ("KArlsruhe Shower Core and Array DEtector") [7]. It is continuously operating since 1996, detecting simultaneously the three main components of air showers. A 200×200 m^2 scintillator array measures the electromagnetic and muonic components ($E_\mu > 0.23$ GeV). The central detector system combines a large hadron calorimeter, measuring the energy, as well as point and angle of incidence for hadrons with energies $E_h > 50$ GeV [8], with several muon detection systems ($E_\mu > 0.49$, 2.4 GeV) [9]. In addition, high-energy muons are measured by an underground muon tracking detector equipped with limited streamer tubes ($E_\mu > 0.8$ GeV) [10].

Results of the KASCADE experiment are summarized in Sects. 2 - 4. In several astrophysical models a transition from galactic to extragalactic cosmic radiation is expected at energies from 10^{17} to 10^{18} eV. A particularity in the energy spectrum in this range is the second *knee* at about 400 PeV [1, 2]. The KASCADE-Grande experiment operates in this energy region, recent results will be reported in Sect. 5. An alternative method to investigate high-energy cosmic rays is the detection of radio signals from air showers, the status of the LOPES experiment will be discussed in Sect. 6.

2. High-energy interactions and air showers

Addressing astrophysical questions with air-shower data necessitates the understanding of high-energy interactions in the atmosphere. The interpretation of properties of primary radiation derived from air-shower measurements depends on the understanding of the complex processes during the cascade development. Recent investigations indicate inconsistencies in the interpretation of air shower data [11, 12, 2]. Thus, one of the goals of KASCADE is to investigate high-energy interactions and to improve contemporary models to describe such processes. The program CORSIKA [13] is applied to calculate the development of extensive air showers. It contains several models to describe hadronic interactions at low and high energies. Their predictions are compared with experimental results in order to check their correctness.

Studies of the shower development in the atmosphere have been performed with the multi-detector set-up and interaction models have been improved [14, 15, 16, 17, 18, 19, 20]. A valuable tool to test high-energy interaction models are correlations between different shower components [21, 22]. A couple of years ago some models like SIBYLL 1.6, DPMJET 2.5, or NEXUS 2 failed to describe the measurements of particular correlations. On the other hand, for contemporary models like QGSJET 01, SIBYLL 2.1, or DPMJET 2.55, the KASCADE measurements are compatible with predictions for various correlations between the electromagnetic, muonic, and hadronic components, i.e. the measurements are bracketed by the extreme assumptions of primary protons and iron nuclei [21, 22]. While in previous analyses pure proton or iron compositions have been assumed as extreme cases, at present, more detailed analyses are

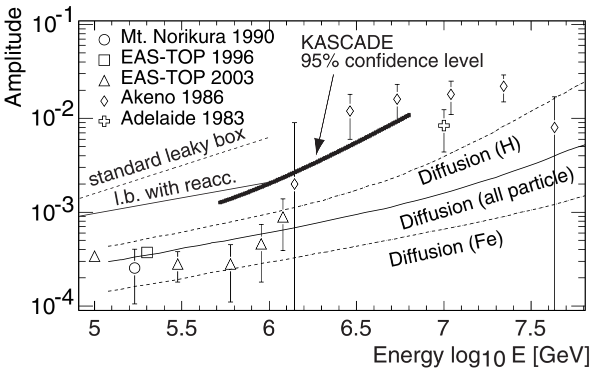

Figure 1. Rayleigh amplitudes as function of energy for various experiments, for references see [32]. Additionally, model predictions for Leaky Box models [33] and a diffusion model [34] are shown. For the latter, the lines indicate the expected anisotropy for primary protons, iron nuclei, and all particles.

performed [22, 23]. They take into account the spectra for elemental groups as obtained from investigations of the electromagnetic and muonic components (see below) and reveal deviations between measurements and simulations for the hadronic component of the order of 10% to 20%.

In conclusion, the models QGSJET 01 [24], SIBYLL 2.1 [25], and DPMJET 2.55 [26] seem to be the most reliable models to describe high-energy hadronic interactions. However, also they are not able to describe the data fully consistently [27]. This illustrates the possibility of experiments like KASCADE, which are able to study details of high-energy interactions in the atmosphere and indicates the progress made in this field during the last decade. At the same time, this stimulates new efforts, with the objective to improve the present interaction models. Examples are new theoretical concepts included in the QGSJET model [28], or the investigations of dedicated changes of physical parameters like the inelastic proton-proton cross-section or the inelasticity of hadronic interactions on air-shower observables [29, 30]. The latter indicate that variations of interaction parameters within the error bounds of accelerator measurements yield significant and measurable changes in the air shower development [31].

3. Cosmic-ray anisotropy

Supernova remnants, such as Cassiopeia A, have been observed in electromagnetic radiation in a wide energy range up to TeV-energies. Calculations indicate that the observed multi-wavelength spectra are consistent with the acceleration of cosmic-ray electrons and hadrons in supernova remnants [35]. Recent observations by the H.E.S.S. experiment reveal a shell structure of the supernova remnant RXJ-1713 and an energy spectrum of γ-rays $\propto E^{-2.2}$ in agreement with the idea of particle acceleration in a shock front [36].

Also, of great interest is to study the arrival direction of charged cosmic rays to search for potential point sources. The arrival directions of showers with energies above 0.3 PeV covering a region from 10° to 80° declination have been investigated with KASCADE [37]. No significant excess has been observed neither for all showers, nor for muon-poor events. The analysis has been deepened by investigating a narrow band (±1.5°) around the Galactic plane. Also circular regions around 52 supernova remnants and 10 TeV-γ-ray sources have been studied. None of the searches provided a hint for a point source, neither by taking into account all events, nor selecting muon-poor showers only. Upper limits for the fluxes from point like sources are determined to be around 10^{-10} m^{-2}s^{-1}. In addition, no clustering of the arrival direction for showers with primary energies above 80 PeV is visible.

While the search for point sources is related to the investigation of cosmic-ray acceleration sites, the large scale anisotropy is expected to reveal properties of the cosmic-ray propagation. The Rayleigh formalism is applied to the right ascension distribution of extensive air showers measured by KASCADE [32]. No hints of anisotropy are visible in the energy range from 0.7 to 6 PeV. This accounts for all showers, as well as for subsets containing showers induced by

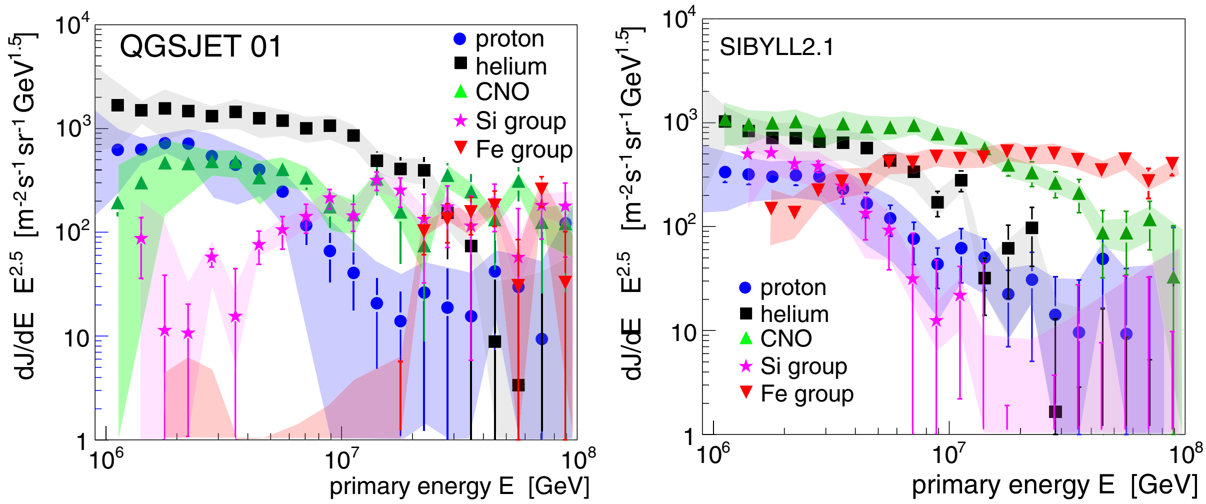

Figure 2. Energy spectra for five cosmic-ray mass groups for measurements interpreted with two different models to describe high-energy hadronic processes in the atmosphere: QGSJET (left) and SIBYLL (right) [27]. The bands represent systematic errors.

predominantly light or heavy primary particles. Upper limits for Rayleigh amplitudes are shown in Fig. 1. The increase of the amplitudes as function of energy is predicted by calculations using a diffusion model to describe the cosmic-ray propagation in the Galaxy [34]. This indicates that leakage from the Galaxy plays an important part during cosmic-ray propagation and most likely, the leakage is also (partly) responsible for the origin of the *knee*. On the other hand, simple Leaky-Box models seem to be ruled out by the measurements [32, 38, 39].

4. Energy spectra and mass composition of cosmic rays

The main objective of KASCADE is to determine the energy spectra and mass composition of cosmic rays. The problem has been approached from various points of view. It could be shown that a *knee* exists in all three main shower components, i.e. electrons, muons, and hadrons at energies $\approx 4-5$ PeV [40]. The primary energy spectrum could be established based on the electromagnetic and muonic [41] as well as the hadronic and muonic components [42]. An analysis of muon densities showed that the *knee* in the all-particle spectrum is caused by a suppression of light elements [43]. Analyses of the electromagnetic and muonic shower components [44], the hadronic and muonic components [45], as well as various combinations of them [11] indicate an increase of the mean logarithmic mass of cosmic rays as function of energy in the *knee* region. The longitudinal development of the muonic shower component is studied with the muon tracking detector of the KASCADE-Grande experiment [46]. The measured flux of unaccompanied hadrons at ground level has been used to derive the spectrum of primary protons [47]. The resulting flux follows a single power law in the energy range from 100 GeV to 1 PeV and is compatible with direct measurements.

An advanced analysis is founded on the measurement of the electromagnetic and muonic shower components [27]. It is based on the deconvolution of a two-dimensional electron muon number distribution. Unfolding is performed using two hadronic interaction models (QGSJET 01 and SIBYLL 2.1) to interpret the data. The spectra obtained for five elemental groups are displayed in Fig. 2. They exhibit sequential cut-offs in the flux for the light elements. For both models a depression is visible for protons around 3 to 4 PeV and at higher energies for helium nuclei. The systematic differences in flux for the spectra derived with QGSJET and SIBYLL amount to a factor of about two to three. The silicon and iron groups show a rather unexpected

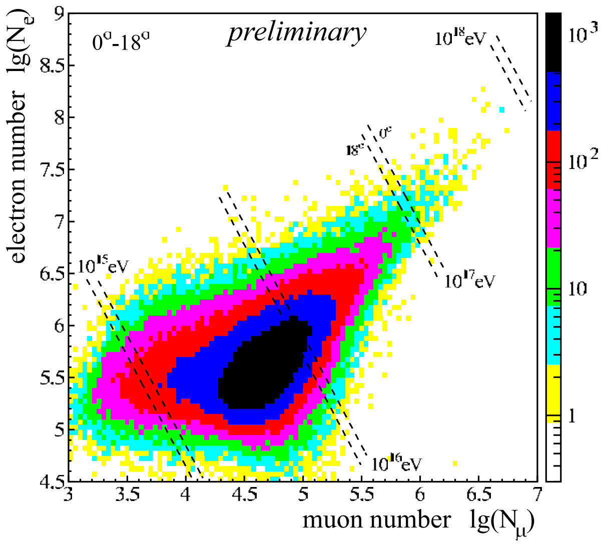

Figure 3. Reconstructed number of electrons as function of the number of muons. The dashed lines indicate estimates for the primary energy for showers with zenith angles of 0° and 18°. Parallel to the lines light elements are at the top and heavy elements at the bottom of the distribution [56].

behavior for both models. The increase of the flux for both groups (QGSJET) and the early cut-off for the silicon group (SIBYLL) is not compatible with contemporary astrophysical models. The discrepancies are attributed to the fact that none of the models is able to describe the observed data set in the whole energy range consistently [27].

Despite of the discrepancies, the spectra compare well to the results obtained by the EAS-Top experiment [48] and extend the results of direct measurements to high energies [49]. Considering the energy range above 10 GeV, at least a qualitative picture of the energy spectra for individual mass groups emerges: the spectra seem to be compatible with power laws with a cut-off at high energies. The cut-off behavior indicated by the measurements is reflected by theoretical considerations taking into account the maximum energy attained during acceleration in supernova remnants [50] or diffusive propagation of cosmic rays in the Galaxy [51].

5. Towards the second knee and the transition to extragalactic cosmic rays

Energy spectra have been reconstructed with KASCADE data up to energies of 100 PeV. At these energies statistical errors start to dominate the overall error. To improve this situation, the experiment has been enlarged. Covering an area of 0.5 km^2, 37 detector stations, containing 10 m^2 of plastic scintillators each, have been installed to extend the original KASCADE set-up [52]. Regular measurements with this new array and the original KASCADE detectors, forming the KASCADE-Grande experiment, are performed since summer 2003 [53]. In parallel, a flash ADC system is being developed to measure the time structure of air showers [54]. The objective is to reconstruct energy spectra for groups of elements up to 10^{18} eV [55], covering the energy region of the second *knee*, where the galactic cosmic ray spectrum is expected to end [39].

First analyses extend the lateral distributions of electrons and muons up to 600 m [56, 57]. A measured two-dimensional shower size spectrum is shown in Fig. 3, the number of electrons is plotted as function of the number of muons. To guide the reader, the dashed lines indicate an estimated primary energy. One recognizes that already now with this data set, based on one year of measurements, energies close to 10^{18} eV are reached. It is planned to conduct an unfolding analysis, similar to the one described above, and reveal the energy spectra for groups of elements up to 10^{18} eV.

6. Radio emission from air showers

Radio emission from air showers is known since the 1960ies [58]. Most likely its origin are electrons deflected in the geomagnetic field and emitting synchrotron radiation in the

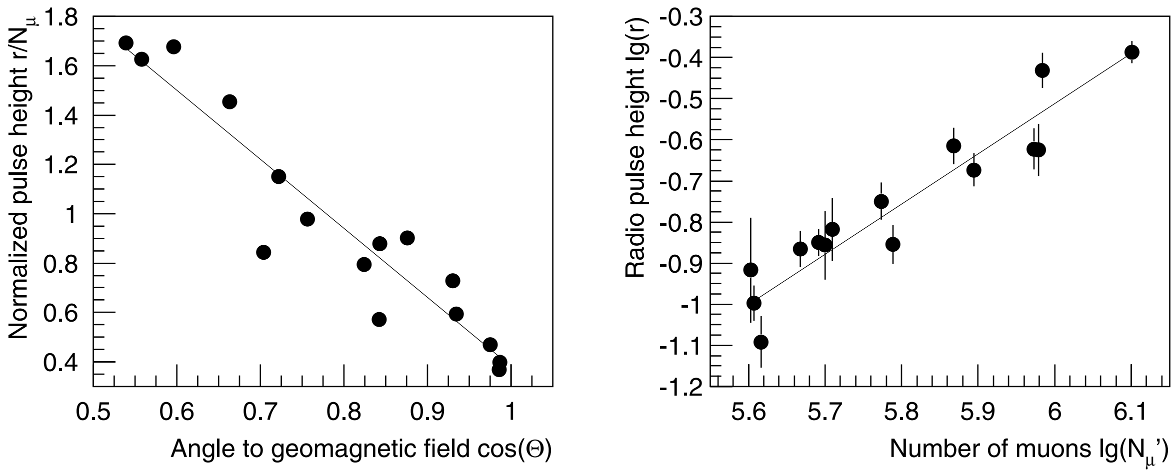

Figure 4. Dependence of the measured radio signal yield on the angle between the geomagnetic field and the shower axis (*left*) and the number of muons in the shower (*right*).

radio frequency range [59]. Calculations show, that on ground level signals in the range of $\sim \mu$V/(m MHz) are expected at frequencies of a few tens of MHz and distances to the shower core smaller than 250 m [60]. The LOPES experiment registers radio signals in the frequency range from 40 to 80 MHz [61]. In this band are few strong man made radio transmitters only, the emission from air showers is still strong (it decreases with frequency), and background emission from the Galactic plane is still low. An active short dipole has been chosen as antenna. An inverted V-shaped dipole is positioned about 1/4 of the shortest wavelength above an aluminum ground plate. In this way a broad directional beam pattern is obtained. Thirty antennas have been installed at the site of the KASCADE-Grande experiment [62]. LOPES is triggered on large air showers detected with KASCADE-Grande. All antennas, including the complete analog electronic chain, have been individually calibrated with a reference radio source [63].

One of the most important results is the dependence of the radio signal pulse height on the angle between the shower axis and the geomagnetic field [64, 65]. The measured radio pulse height normalized to the number of muons in the respective shower is presented as function of the cosine of the angle with respect to the geomagnetic field in Fig. 4 (*left*). The signal yield clearly depends on the orientation with respect to the magnetic field. This can be interpreted as confirmation for the proposed origin of the radio frequency radiation, i.e. synchrotron radiation in the geomagnetic field. It is planned to measure the polarization of the radio signal as well, this will clarify the situation. The measured radio pulse height is shown as function of the registered number of muons in Fig. 4 (*right*). The radio signal yield increases as function of muon number. The latter is strongly correlated to the shower energy (nearly independent of the mass of the primary), the range depicted corresponds roughly to about 10^{17} to $6 \cdot 10^{17}$ eV.

In addition, alternative antenna designs are investigated [66]. The experimental work is accompanied by efforts to include models for the radio signal generation into the standard air shower simulation program CORSIKA [67].

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