Astrophys. Space Sci. Trans., 7, 295–301, 2011
www.astrophys-space-sci-trans.net/7/295/2011/
doi:10.5194/astra-7-295-2011

Astrophysics and Space Sciences Transactions

Cosmic rays in the knee energy range

A. Haungs

Karlsruhe Institute of Technology (KIT) - Helmholtz Sector, Institut für Kernphysik, Germany

Received: 16 December 2010 – Accepted: 15 March 2011 – Published: 30 August 2011

Abstract. In the energy range of the so called 'knee' between 100 TeV and 1 EeV one expects to identify the end of the galactic origin of cosmic rays. Only for the lowest energies a direct detection with instruments on high-altitude, long-flying balloons are possible. Measurements of the high-energy particles are performed indirectly via the detection of extensive air showers by extended arrays of particle or Cherenkov light sensitive detectors. Multidimensional analyses of the air shower data indicate a distinct knee in the energy spectra of light primary cosmic rays at few PeV and an increasing dominance of heavy ones towards higher energies. This provides implications for discriminating astrophysical models of the origin of the knee and of the physics of the transition from galactic to extragalactic cosmic ray origin. Where around 1 PeV many experiments were in operation and have given valuable results in the last decade, at higher energies there was a lack of experimental efforts. To improve the reconstruction quality and statistics at energies from 10 to 1000 PeV, where the transition can be expected, presently several experiments are in operation or going to be in operation. First results of these experiments, as well as perspectives of future efforts in this energy range will be discussed.

1 Introduction

The all-particle energy spectrum of cosmic rays exhibits a distinctive discontinuity at few PeV, known as the knee, where the spectral index changes from -2.7 to approximately -3.1 (Fig. 1). This feature has been discovered more than half a century ago by Kulikov and Khristiansen of the Moscow State University (Kulikov and Khristiansen, 1958) within studies of the intensity spectrum of the content of charged particles of extensive air showers, which roughly reflects the primary energy. Another feature in the striking power-law behavior of the spectrum is visible around $4-10 \cdot 10^{18}$ eV, known as the ankle, where the spectral index of the particle flux changes back to approximately -2.7 (Nagano and Watson, 2000).

Up to energies of a few 10^{14} eV direct measurements via balloon and satellite based instruments are performed. But, above these energies direct measurements are hardly possible due to the low flux. Thus indirect measurements observing extensive air showers (EAS) attempt to reveal the structure of the spectrum. Figure 2 sketches the various possibilities in measuring extensive air showers. Sophisticated experiments are characterized by applying more than one technique and observing several EAS techniques simultaneously in order to obtain as much information on the individual EAS as possible.

The key questions of the origin of this knee are still not convincingly solved. Astrophysical scenarios like the change of the acceleration mechanisms at the cosmic ray sources (supernova remnants, pulsars, etc.) or effects of the transport mechanisms inside the Galaxy (diffusion with escape probabilities) are conceivable for the origin of the knee as well as particle physics reasons like a new kind of hadronic interaction inside the atmosphere or during the transport through the interstellar medium. An overview on the zoo of these theoretical models is given in reference (Hörandel, 2004). It is obvious that only detailed measurements covering the full energy range of the knee from 10^{14} eV to 10^{18} eV and analyses of the primary energy spectra for the different incoming particle types can validate or disprove some of these models.

Despite of numerous EAS studies with various different experimental set-ups in the last decades, this demand could be never accomplished, mainly due to the weak mass resolution of the measured shower observables (Haungs et al., 2003).

Correspondence to: A. Haungs
(haungs@kit.edu)

Published by Copernicus Publications on behalf of the Arbeitsgemeinschaft Extraterrestrische Forschung e.V.

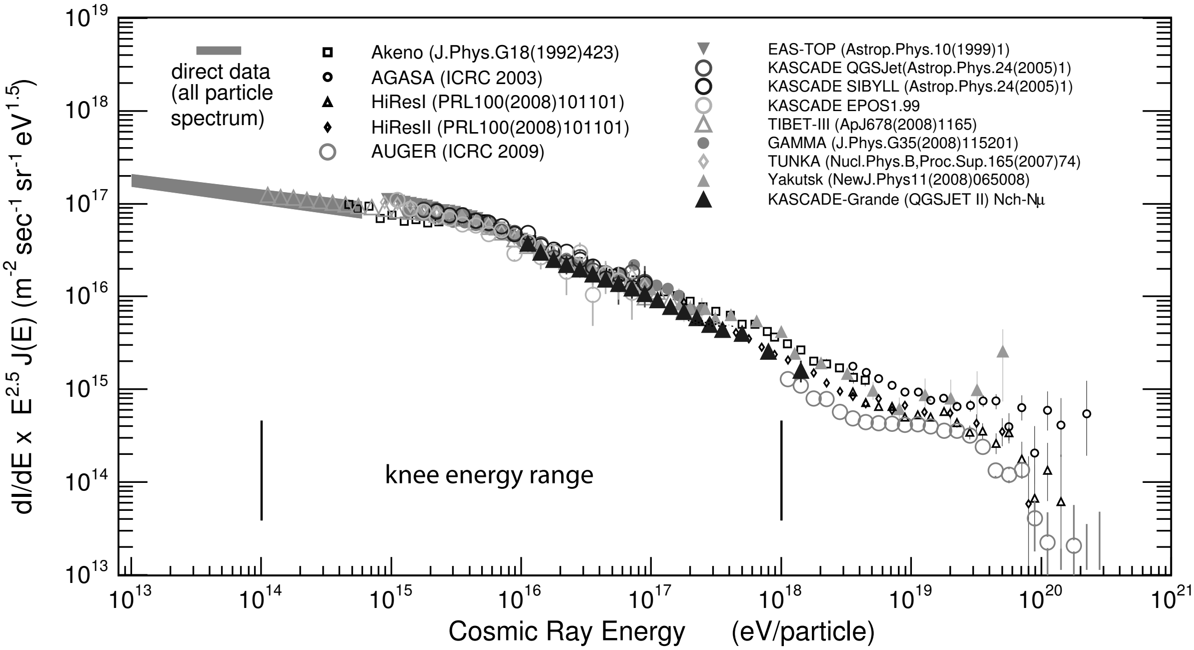

Fig. 1. The all-particle energy spectrum as measured by various experiments. References to the data points are given within the plot; the results of KASCADE-Grande refer to reference (Arteaga et al., 2010).

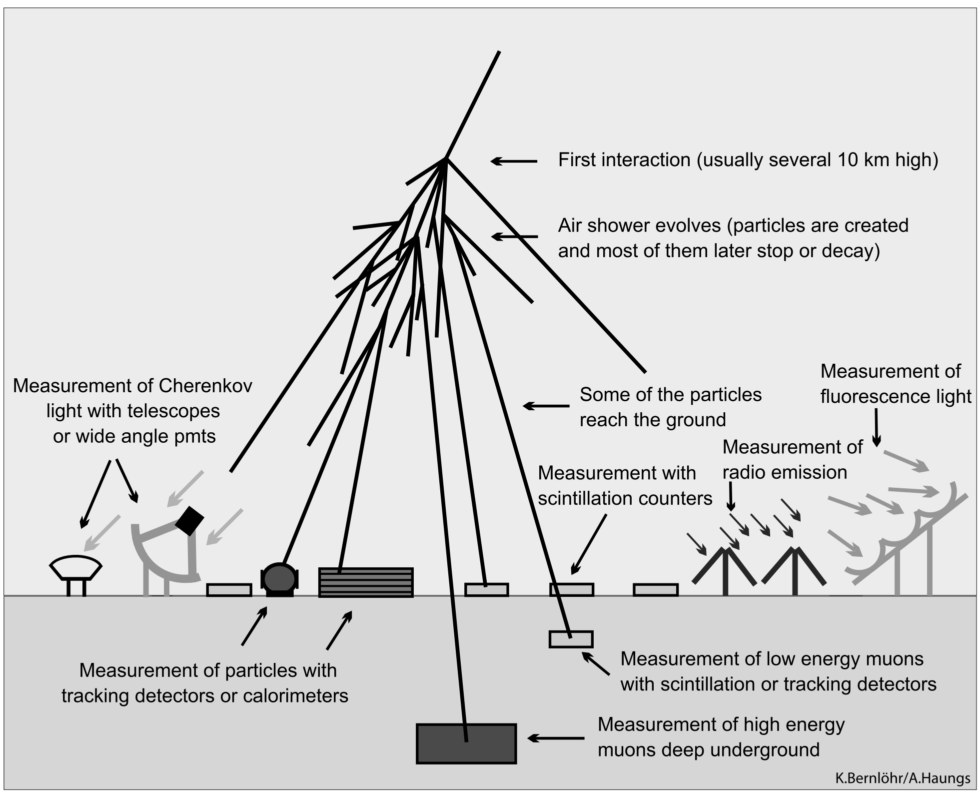

Fig. 2. Sketch of various ways to study experimentally extensive air showers. The fluorescence and radio technique is only efficient for cosmic rays above 100 PeV, and therefore of minor importance for the knee energy range.

The highest energies above the so called ankle at a few EeV are believed to be exclusively of extragalactic origin. The extragalactic component and the possible cut-off (GZK) at c. 100 EeV is subject of the Pierre Auger Observatory (see Abraham et al., 2004) Thus, in the experimentally scarcely explored region between the (first) knee and the ankle there are two more peculiarities of the cosmic ray spectrum expected: (i) A knee of the heavy component which is either expected (depending on the model) at the position of the first knee scaled with Z (the charge) or alternatively with A (the mass) of iron. (ii) A transition region from galactic to extragalactic origin of cosmic rays, where there is no theoretical reason for a smooth crossover in slope and flux. Close to 10^{18} eV, earlier experiments have claimed a so-called 'second knee' (Bergman and Belz, 2007), where, dependent on the considered astrophysical model, it is allocated to case (i) or (ii), respectively. In order to investigate different scenarios precise EAS measurements of high statistical accuracy are needed for the energy range of 10^{16} and 10^{18} eV, which appears a little bit ignored in the last decades. Meanwhile, more interest arose, mainly due to first results from sophisticated experiments like KASCADE-Grande. In addition, new experimental efforts are performed and a couple of experiments just started to be or will be soon in operation.

Figure 1 summarizes the experimental results related to the all-particle energy spectrum. What will follow in this short review is mainly the discussion of recent experimental findings on the structure and peculiarities of this spectrum in the energy range of the knee. In addition these findings, in particular for the higher energy range, will be discussed in context of astrophysical models for the origin and propagation of cosmic rays.

2 Below the knee

Figure 3 shows the cosmic ray spectra obtained by direct measurements for the different nuclei. The impressing parallelity of the spectra (except at very low energies where the solar modulation affects the spectral shape) is used as argument that the galactic cosmic rays originated from a single acceleration and propagation process within our Milky Way which is valid up to the knee energy. However, recently the CREAM balloon experiment mentioned that the parallelity is violated in case of proton and helium spectra in such a way that the spectra have slightly different slopes and show a slightly concave behaviour, with the consequence that Helium should be the dominant component already before the knee. It is interesting to note, that the CREAM collaboration has assigned this hardening of the proton and helium spectra (Ahn et al., 2010) to a possible change of the acceleration mechanism of cosmic rays.

A second interesting experimental observation concerns anisotropy studies of cosmic rays in the energy range of a few TeV. Here, two large-scale regions with a significant excess

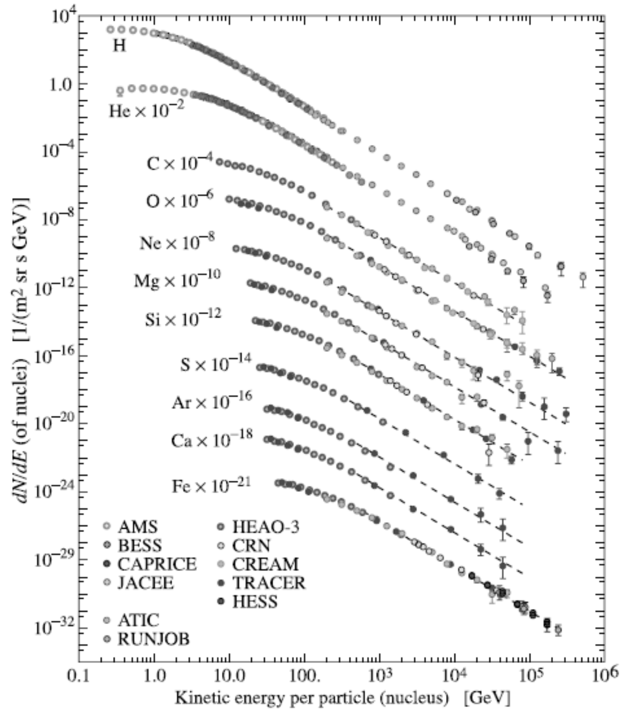

Fig. 3. Compilation of direct measurements of the cosmic ray energy spectrum for different nuclei (from (Nakamura et al., 2010)).

were found by various experiments, more precisely by MILAGRO (Abdo et al., 2008), ICECUBE (Abbasi et al., 2010), TIBET (Amenomori et al., 2006), and Superkamiokande (Guillian et al., 2007). In particular, the MILAGRO collaboration could determine both, the large-scale anisotropy and, based on filtering out the large variations, also small scale variations in the flux (Abdo et al., 2009). The source of this large-scale anisotropy is as unknown as its possible influence to higher energies, i.e. the knee energy range.

3 The knee

From the manifold experimental efforts in studying the knee of the last decades, the KASCADE experiment was probably the most sophisticated. Hence, this chapter will start with a short review on the results of this experiment. The KASCADE experiment (Antoni et al., 2003) introduced a new quality of investigations of the knee feature in the energy spectrum, due to its high precision in reconstructing the total electron and muon number separately in individual EAS. Additionally, for each event hadron and high-energy muon information is available. The data analyses aim to reconstruct the energy spectra of individual mass groups taking into account not only different shower observables, but also their correlation on an event-by-event basis. The content of each cell of the two-dimensional spectrum of reconstructed

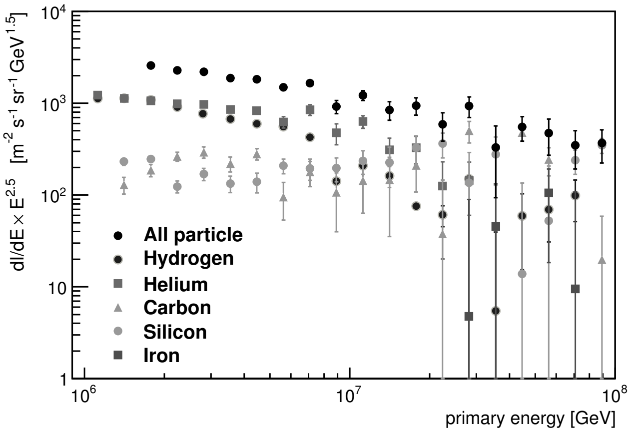

Fig. 4. All-particle spectrum and individual mass spectra of KASCADE as result of the unfolding procedure based on the hadronic interaction model EPOS 1.99 (from Finger, 2010; Haungs et al., 2010).

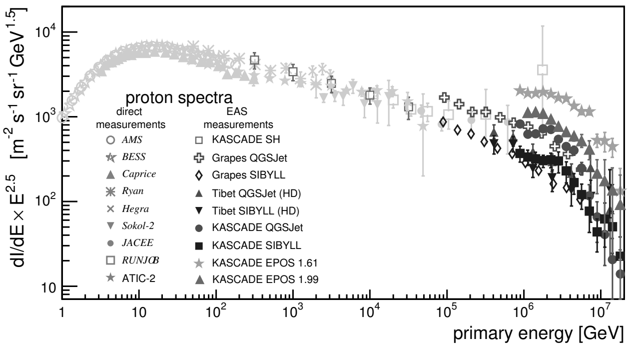

Fig. 5. Compilation of direct and indirect measurements of the cosmic ray energy spectrum of primary protons. In case of KASCADE the results of different models are included (Haungs et al., 2010).

electron number vs. muon number $g(y)$ is the sum of contributions from the individual primary elements. Hence the inverse problem $g(y) = \int K(y,x)\,p(x)\,dx$ with $y = (N_e, N_\mu^{\mathrm{tr}})$ and $x = (E, A)$ has to be solved, and with known $p(x)$ the spectra of individual masses can be built. The kernel function is obtained by Monte Carlo simulations on basis of (different) hadronic interaction models as options embedded in CORSIKA. CORSIKA is a sophisticated air shower simulation tool package (Heck et al., 1998), which was developed in the frame of the KASCADE experiment and which meanwhile is worldwide used.

By applying these procedures (with the assumption of five primary mass groups) to the experimental data energy spectra for 5 individual mass groups are obtained and the sum of these spectra results in the all particle spectrum as shown in Fig. 1) (Apel et al., 2005). Concerning the individual spectra a knee like feature was clearly detected in the spectra of primary proton and helium. This demonstrated that the knee feature originates from a decreasing flux of the light primary particles. The described analysis was repeated by using different hadronic interaction models where these findings were confirmed (Apel et al., 2010; Haungs et al., 2010). Figure 4 shows as an example the results of KASCADE based on the newest version of the hadronic interaction model EPOS (Werner et al., 2006). This model interprets the measurements as composed mainly by light primaries, but interestingly the slopes between the proton and Helium spectra are slightly different in such a way that around 1 PeV Helium gets more abundant than protons, which is in accordance with the measurements by the CREAM balloon experiment.

Comparing the unfolding results based on the different hadronic interaction models, similar structures of the individual spectra as well as the all-particle spectrum agree nicely, but the relative abundances of the primary mass groups (composition) differ significantly. Thus presently it is not yet possible to pin down definitely the mass composition. Modeling the hadronic interactions underlies assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by discrepancies in the resulting composition. The differences in the total energy appear to be comparatively smaller and are less model dependent.

Crucial parameters of the modeling of hadronic interaction models which can be responsible for these inconsistencies are the total nucleus-air cross-section and the parts of the inelastic and diffractive cross sections leading to shifts of the position of the shower maximum in the atmosphere, and therefore to a change of the muon and electron numbers as well as to their correlation on single air shower basis. The multiplicity of the pion generation at all energies at the hadronic interactions during the air shower development is also a semi-free parameter in the air-shower modeling as accelerator data have still large uncertainties. Arbitrary changes of free parameters in the interaction models will change the correlation of all shower parameters. Tests using KASCADE observables (Antoni et al., 1999; Apel et al., 2009), which are measured independently of those used in the unfolding procedure, give further constraints, in particular by investigating correlations of the hadronic shower component with electron or muon numbers. The aim is to provide hints for the model builder groups how the parameters (and the theory) should be modified in order to describe all the data consistently. Combining all the correlations, the final observables of the showers have not to be different by more than $\approx 15\%$ to be consistent with the data. This requires rather a fine-tuning of the free parameters in the simulation of the hadronic interactions than a need on new physics. That this is true can be seen in Fig. 5 where the resulting proton spectra are compared with direct measurements, where many data are available. Here, most of the results are in the range of the statistical uncertainty of the extrapolation of direct measurements.

In summary, the KASCADE results provide clear hints for a rigidity dependence of the knee feature, which automatically leads to an increasing heavier mean mass of the composition passing the knee (De Donato and Medina-Tanco, 2009). But what is the dominant primary mass group at the knee? This is still an open question, and the KASCADE and TIBET (Amenomori et al., 2008) collaborations interpret their data in a different way despite their proton fluxes (see Fig. 5) are in good agreement. Direct measurements of high-energy cosmic rays, which are able to determine the composition in a model independent way, may be possible in future and could give an answer to this question. In addition, the GRAPES (Tanaka et al., 2008) experiment in India, whose detector installation is similar to KASCADE, but located at higher altitude, will reach lower primary energies, providing an overlap with direct measurements.

Another open question is the 'sharpness' of the knee. Some experiments, like TIBET (Amenomori et al., 2008) or TUNKA (Korosteleva et al., 2007), e.g. claim explicitly that they see a sharp knee which can be explained by a considerable contribution to the overall bulk of cosmic rays stemming from a near-by single source (Erlykin and Wolfendale, 2005). The knee of the underlying 'standard' spectrum should be smeared out as it is originating from many sources (SNR's) and also by propagation effects.

4 Above the knee

For the still less explored energy range between knee and ankle there are now new results available from the KASCADE-Grande (Apel et al., 2010a) experiment, which is an extension of the former KASCADE installation, still allowing the independent measurement of the muon content of the EAS. In particular this possibility to reconstruct the total muon number for Grande measured showers is the salient feature of KASCADE-Grande compared to other experiments in this energy range.

Figure 1 shows the reconstructed all-particle spectrum which was communicated this year as a first result of KASCADE-Grande (Bertaina et al., 2010). For displaying the very interesting details of the shape of the spectrum a residual plot was constructed in order to see the deviation from a flux proportional to $E^{-3.015}$ (see Fig. 6) which is the index obtained by fitting the middle part of the spectrum. Two interesting features show up, one is a concavity above 10^{16} eV and another one is a small break at $\approx 10^{17}$ eV.

For a discussion of the astrophysical implications of these findings in some more details, Figure 7 by Michael Hillas (Hillas, 2005) depicts a possible scenario. In order to reproduce the measured spectrum, before the KASCADE-Grande results appeared, Hillas proposed a 'component B' of the spectrum additionally to the rigidity dependent main galactic component. It fills the gap between the knee and the ankle before the extragalactic component gets efficient. This

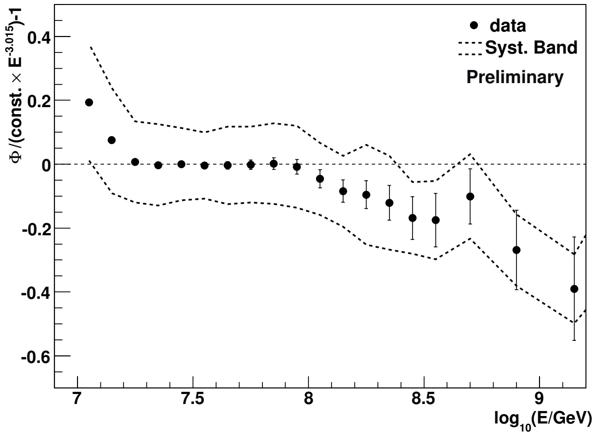

Fig. 6. Residual plot for the reconstructed all-particle energy spectrum obtained from KASCADE-Grande. The systematic error band is also shown (dotted lines). The plot is taken from reference (Arteaga et al., 2010).

model is in contradiction to the 'dip model' (Berezinsky et al., 2006), where the rigidity dependent main galactic component is directly overtaken from a proton dominant extragalactic component already at 10^{17} eV. Here, the ankle is generated by an extragalactic feature.

The concavity or hardening of the spectrum seen by KASCADE-Grande can be explained in terms of the rigidity dependent main bulk of cosmic rays responsible for the knee, see Fig. 7. According to the relative abundance of the heavy component the significance of this hardening can increase or decrease. By that, the KASCADE-Grande finding also can serve as a hint to the composition around 10^{16} eV. The weak knee-like feature close to 10^{17} eV seen by KASCADE-Grande is also in agreement with the rigidity model as the position of the structure is at an energy where one expect the knee of the iron component. But, both findings are still in agreement with both contradicting astrophysical models. Crucial for clarifying the situation are detailed studies of the composition in this energy range where KASCADE-Grande has a rich potential.

For completion of the present experimental situation, results of the GAMMA experiment (**?**) will be mentioned. They reported about a peak in the spectral shape close to 10^{17} eV (see Fig. 1) which can be explained by the iron component of the mentioned near-by single source of cosmic ray origin. Such a strong peak is not confirmed by the KASCADE-Grande result and its existence, at least in such a significant appearance, is still under discussion.

In near future, new experiments will be in operation (or are already in operation) which will give new insights in the energy range of the transition region. We can expect a deeper insight in the physics of cosmic rays for example by

– KASCADE-Grande: Sophisticated analysis methods of the available data enables detailed composition studies (Arteaga et al., 2010).

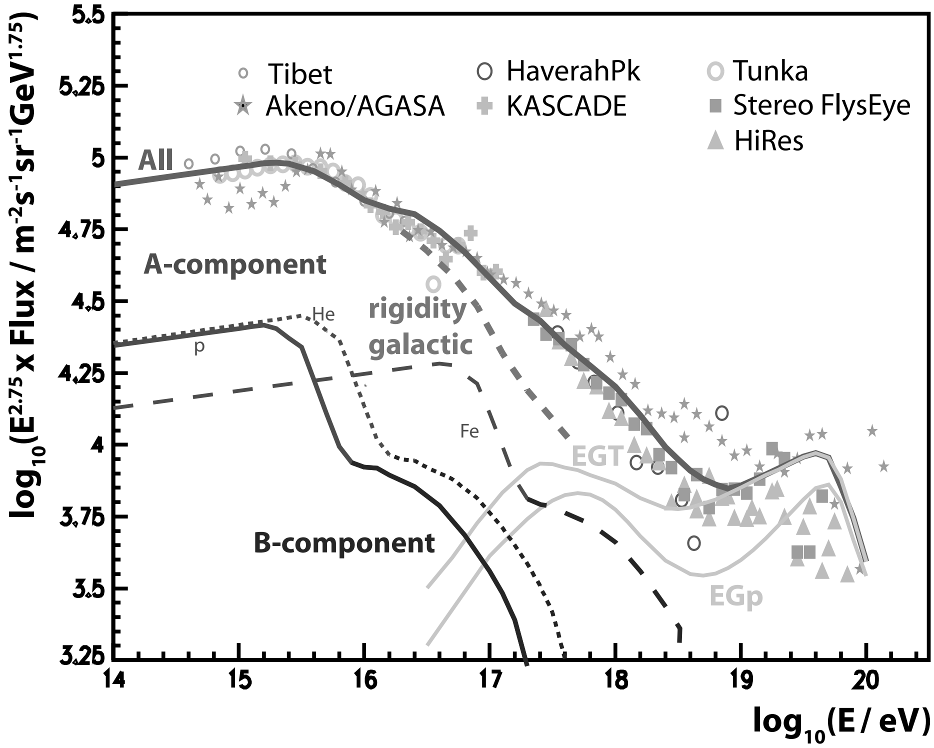

Fig. 7. Possible scenario for explaining structures of the cosmic ray all-particle energy spectrum. To the standard galactic component 'A' a component B is added closing the gap to the extragalactic component at highest energies (EG, where EGp is the proton component and EGT stands for total EG contribution) (Hillas, 2005).

– TUNKA: An extension of the Cherenkov-Array TUNKA is in operation and allows access to energies up to a few hundred PeV (Korosteleva et al., 2007).

– ICETOP/ICECUBE: A combination of the on-ice particle detector array with the muon-sensitive in-ice neutrino detector will allow detailed composition studies for this energy range (Waldenmaier et al., 2010).

– Pierre Auger Observatory Enhancements: Specialized fluorescence telescopes in combination with a denser surface array, underground muon detectors and possibly a radio antenna array will serve as a super-hybrid detector for the energy range below the ankle (Blümer et al., 2010).

5 Conclusions

In recent years experimental as well as theoretical studies have established that the knee covers a large range in energy, namely from 100 TeV up to 1 EeV. In particular, the higher energy range experienced recently larger attention as the still unknown mechanism of the transition from galactic to extragalactic origin of cosmic rays affects the interpretation of the measurements of the highest energy cosmic particles. Sophisticated experiments already in operation or being soon in operation will provide in next couple of years a deeper insight in the miracles of the cosmic ray energy spectrum.

Acknowledgements. The author wants to express that the present article reflects a personal view on the subject, which is far from completeness. The author would like to thank the organizers of the ECRS 2010 for invitation and all the colleagues in the field, in particular from the KASCADE-Grande Collaboration, for stimulating discussions.

Edited by: K. Scherer
Reviewed by: three anonymous referees

References

Abbasi, R. et al. (IceCube Collaboration): Measurement of the Anisotropy of Cosmic Ray Arrival Directions with IceCube, Astroph. J. Lett., 718, 194, 2010.

Abdo, A. A. et al. (Milagro Collaboration): Discovery of Localized Regions of Excess 10-TeV Cosmic Rays, Phys. Rev. Lett., 101, 221101, 2008.

Abdo, A. A. et al. (Milagro Collaboration): The Large Scale Cosmic-Ray Anisotropy as Observed with Milagro, Astrophys. J., 698, 2121, 2009.

Abraham, J. et al. (Pierre Auger Collaboration): Properties and performance of the prototype instrument for the Pierre Auger Observatory, Nucl. Instrum. Meth. A, 523, 50, 2004.

Ahn, H. S. et al. (CREAM Collaboration): Discrepant hardening observed in cosmic-ray elemental spectra, Astrophys. J., 714, L89, 2010.

Amenomori, M. et al. (TIBET AS-gamma Collaboration): Anisotropy and Corotation of Galactic Cosmic Rays, Science, 314, 439, 2006.

Amenomori, M. et al. (TIBET AS-gamma Collaboration): The All-particle spectrum of primary cosmic rays in the wide energy range from 10^{14} eV to 10^{17} eV observed with the Tibet-III air-shower array, Astrophys. J., 678, 1165, 2008.

Antoni, T. et al. (KASCADE Collaboration): Test of high-energy interaction models using the hadronic core of EAS, J. Phys. G: Nucl. Part. Phys., 25, 2161, 1999.

Antoni, T. et al. (KASCADE Collaboration): The Cosmic ray experiment KASCADE, Nucl. Instrum. Meth. A, 513, 490, 2003.

Apel, W.-D. et al. (KASCADE Collaboration): KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems, Astrop. Phys., 24, 1, 2005.

Apel, W.-D. et al. (KASCADE Collaboration): A test of the hadronic interaction model EPOS with air shower data, J. Phys. G: Nucl. Part. Phys., 36, 035201, 2009.

Apel, W.-D. et al. (KASCADE Collaboration): Energy spectra of elemental groups of cosmic rays: Update on the KASCADE unfolding analysis, Astrop. Phys., 31, 86, 2010.

Apel, W.-D. et al. (KASCADE-Grande Collaboration): The KASCADE-Grande Experiment, Nucl. Instrum. Meth. A, 620, 202, 2010a.

Arteaga, J. C. et al. (KASCADE-Grande Collaboration): The KASCADE-Grande experiment: measurements of the all-particle energy spectrum of cosmic rays, ISVHECRI, 2010.

Berezinsky, V., Gazizov, A., Grigorieva, S.: On astrophysical solution to ultrahigh-energy cosmic rays, Phys. Rev., 74, 043005, 2006.

Bergman, D. R. and Belz, J. W.: Cosmic Rays: The Second Knee and Beyond, J. Phys. G: Nucl. Part. Phys., 34, 359, 2007.

Bertaina, M. et al. (KASCADE-Grande Collaboration): The cosmic ray energy spectrum in the range $10^{16} - 10^{18}$ eV measured by KASCADE-Grande, Astrophys. Space Sci. Trans., 7, 229, 2011.

Blümer, J. et al. (Pierre Auger Collaboration): The northern site of the Pierre Auger Observatory, New J. Phys., 12, 035001, 2010.

De Donato, C. and Medina-Tanco, G.: Experimental constraints on the astrophysical interpretation of the cosmic ray Galactic-extragalactic transition region, Astrop. Phys., 32, 253, 2009.

Erlykin, A. D. and Wolfendale, A. W.: The origin of cosmic rays, J. Phys. G: Nucl. Part. Phys., 31, 1475, 2005.

Finger, M.: Reconstruction of energy spectra for different mass groups of high-energy cosmic rays, PhD Karlsruhe Institute of Technology, in press, 2010; private communication.

Garyaka, A.P. et al. (GAMMA Collaboration): All-particle primary energy spectrum in the 3-200 PeV energy range, J.Phys.G:Nucl.Part.Phys. **35** 115201, 2008.

Guillian, G. et al. (Super-Kamiokande Collaboration): Observation of the anisotropy of 10-TeV primary cosmic ray nuclei flux with the Super-Kamiokande-I detector, Phys. Rev. D, 75, 062003, 2007.

Haungs, A., Rebel, H., and Roth, M.: Energy spectrum and mass composition of high-energy cosmic rays, Rept. Prog. Phys., 66, 1145, 2003.

Haungs, A. et al. (KASCADE-Grande Collaboration): Latest results and perspectives of the KASCADE-Grande EAS Facility, Nucl. Instrum. Meth. A, doi:10.1016/j.nima.2010.11.126, 2010.

Heck, D., Knapp, J., Capdevielle, J. N. et al.: The air shower simulation program CORSIKA, Report FZKA 6019, Forschungszentrum Karlsruhe, 1998.

Hillas, A. M.: Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays?, J. Phys. G: Nucl. Part. Phys., 31, 95, 2005.

Hörandel, J. R.: Models of the knee in the energy spectrum of cosmic rays, Astropart. Phys. 21 241, 2004.

Korosteleva, E. E. et al. (Tunka Collaboration): Measurement of cosmic ray primary energy with the atmospheric Cherenkov light technique in extensive air showers, Nucl. Phys. B, Proc. Sup., 165, 74, 2007.

Kulikov, G. V. and Khristiansen, G. B.: On the size distribution of extensive atmospheric showers, Soviet Physics JETP, 35(8), No.3, 1958.

Nagano, M. and Watson, A. A.: Observations and implications of the ultrahigh-energy cosmic rays, Rev. Mod. Phys., 72, 689, 2000.

Nakamura, K. et al. (Particle Data Group): Review of Particle Physics, J. Phys. G, 37, 075021, 2010.

Tanaka, H. et al. (GRAPES Collaboration): Study on nuclear composition of cosmic rays around the knee utilizing muon multiplicity with GRAPES-3 experiment at Ooty, Nucl. Phys. B, Proc. Sup., 280, 175, 2008.

Waldenmaier, T. et al. (IceCube Collaboration): Cosmic-Ray Detection with ICECUBE-ICETOP, in: Proc. ICATPP conference 2010, Como, Italy, to be published in World Scientific, 2010.

Werner, K., Liu, F. M., and Pierog, T.: Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at RHIC, Phys. Rev. C, 74, 044902, 2006.