Vol. 35 (2004) *ACTA PHYSICA POLONICA B* No 1

ASTROPHYSICS OF THE KNEE IN THE COSMIC RAY ENERGY SPECTRUM*

A. Haungs[a]
T. Antoni[b], W.D. Apel[a], F. Badea[a], K. Bekk[a], A. Bercuci[a]
H. Blümer[a,b], H. Bozdog[a], I.M. Brancus[c], C. Büttner[b]
A. Chilingarian[d], K. Daumiller[b], P. Doll[a], R. Engel[a]
J. Engler[a], F. Fessler[a], H.J. Gils[a], R. Glasstetter[a,†], D. Heck[a]
J.R. Hörandel[b], K.-H. Kampert[a,b,†], H.O. Klages[a], G. Maier[a]
H.J. Mathes[a], H.J. Mayer[a], J. Milke[a], M. Müller[a]
R. Obenland[a], J. Oehlschläger[a], S. Ostapchenko[b], M. Petcu[c]
S. Plewnia[a], H. Rebel[a], A. Risse[e], M. Risse[a], M. Roth[b]
G. Schatz[a], H. Schieler[a], J. Scholz[a], T. Thouw[a], H. Ulrich[a]
J. van Buren[a], A. Vardanyan[d], A. Weindl[a], J. Wochele[a]
J. Zabierowski[e], and S. Zagromski[a]

[a]Institut für Kernphysik, Forschungszentrum Karlsruhe, Karlsruhe, Germany
[b]Institut für Experimentelle Kernphysik, Univ. Karlsruhe, Karlsruhe, Germany
[c]National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
[d]Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia
[e]A. Soltan Institute for Nuclear Studies, 90-950 Łódź, Poland

(Received November 14, 2003)

A brief review is given on the astrophysics of cosmic rays in the PeV primary energy range, *i.e.* the region of the knee.

PACS numbers: 96.40.De, 96.40.Pq, 98.70.Sa

1. Introduction

The all-particle energy spectrum of cosmic rays shows a distinctive feature at a few PeV, known as the knee, where the spectral index of a power-law dependence changes from −2.7 to approximately −3.1. At that energy direct measurements via balloon or satellite borne experiments are presently hardly possible due to the low flux. But indirect measurements via the

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.
† now at: Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany.

observation of extensive air showers (EAS) have been performed. Despite of more than 50 years of EAS measurements the origin of the knee is still unclarified, due to the difficult but inevitable disentanglement of the reconstruction of the energy and mass of the incoming primary particle with the necessary understanding of the air-shower development in the Earth's atmosphere. This disentanglement remains an important experimental and theoretical challenge. A general introduction to the subject can be found in a recent review [1].

To solve the puzzle of the knee the experimental access is the reconstruction of energy spectra for individual elements (or mass groups), with an accompanying careful investigation of the hadronic interaction mechanisms governing the air-shower development.

In the present contribution a short overview on theoretical ideas of explaining the knee is given. Additionally recent results from the advanced air-shower experiment KASCADE are discussed and compared to astrophysical model predictions. Furthermore the connection of the source of charged cosmic rays with measurements of TeV gamma-rays is outlined. Hadronic interaction models used for the simulation of the air-shower development are needed in all analyses of the data of air-shower experiments. Hence, tests of their validity is a crucial item of the data reconstruction. Details of such investigations are described in the contributions of Engel *et al.* [2] and Milke *et al.* [3] at this symposium.

2. Theoretical attempts for explaining the origin of the knee

Theories on market about the origin of the knee can be grouped in three classes:

1. By acceleration: The knee energy is the maximum energy reached by acceleration of cosmic rays in our galaxy. This maximum energy is defined by the size and magnetic field strength of the acceleration region and depends on the charge Z of the primary particles ($E_{\rm max} \propto Z \times (L \times B)$). For example, Biermann *et al.* [4] proposed a scenario with a two component supernova acceleration, where 'normal' supernovae explode into the interstellar medium and accelerate mainly protons up to approximately 100 TeV and where more massive supernovae exploding into their own stellar wind accelerate also heavier particles up to $Z \times 10^{15}$ eV.

2. By diffusion: The idea is that the magnetic field retains the particles within the Galaxy up to energies at the knee ($E_{\rm max} \approx Z \times 3 \times 10^{15}$ eV). Particles of higher energy would start to escape from our galaxy. A

detailed calculation has been performed by Candia *et al.* [5] starting with a constant source spectrum at 1 TeV (from results of direct measurements) and taking into account a regular plus an overlaying turbulent component of the galactic magnetic field. Fig. 1 shows predictions for the all-particle energy spectrum of cosmic rays for different assumptions of average distances of the sources. Predictions for large scale anisotropies by the diffusion are also given in [5].

3. By hadronic interaction features: Such models assume that a new channel of interaction is opening, either in the interstellar medium or inside our atmosphere. In this new channel a part of the primary energy is dissociated, and therefore unseen in the air-shower. This leads to the reconstruction of too small primary energies. Such a mechanism should start at energies proportional to the mass of the primaries, *i.e.* the knee position should shift in proportion to the atomic number and not to the charge of the primary particles. Possible scenarios are here the production of gravitons in *pp* collisions [6] or interactions of the primaries with heavy relic neutrinos [7]. Most probably such models will be confirmed or excluded by data from the LHC.

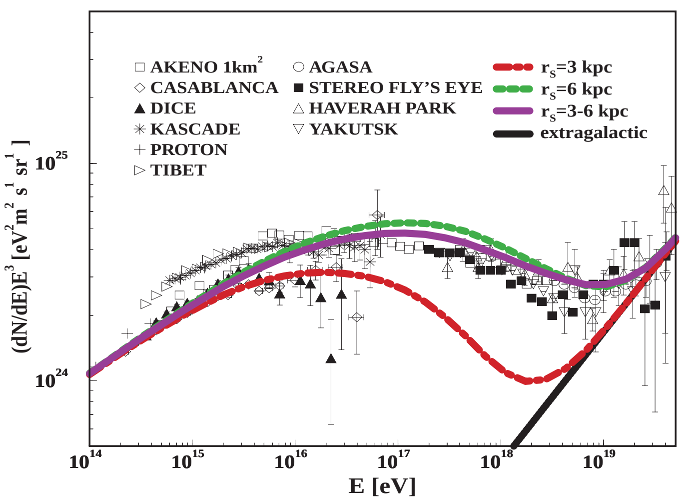

Fig. 1. Comparison of the measured cosmic-ray all-particle energy spectrum with predictions by a diffusion model (from [5]).

To distinguish between these mentioned theories, several burning questions have to be answered by experiments measuring air-showers in the PeV energy range:

- The all-particle energy spectrum and possible fine structures: Is the knee sharp or smooth with exact power laws below and above? At which energy is the position of the knee?
- The chemical composition around the knee: Does it change with energy? Does the mean mass become heavier or lighter?
- Energy spectra of single elements or mass groups: Do all primary mass groups show a knee feature? Do the spectra follow power laws above the knee? Do different primaries exhibit a knee at different energies? If yes, do the positions scale with mass or charge of the primary particles?
- The proton spectrum: Where is the knee of the proton spectrum? Is there more than one knee?
- Isotropy: Are the cosmic rays distributed isotropically over the whole energy range of the knee? Or do large scale anisotropies occur? Are any point source visible?
- Primary photons: Are there high-energy gamma rays as primary particles? If yes, is their origin diffuse or do they originate from point sources?
- Air-shower development: Is the air-shower development driven by the hadronic interactions of high-energy particles well understood?

Due to the indirect nature of EAS measurements the latter point hampers a definite conclusion on most of the above mentioned questions. Here a co-operation between the accelerator and cosmic-ray physics communities is highly desired [8].

3. Results of the KASCADE experiment

KASCADE (KArlsruhe Shower Core and Array DEtector) is an air-shower experiment with a sophisticated detector set up for detailed investigations of primary cosmic rays in the energy range of the knee. For the reconstruction of the energy and mass of the primary particles and for the investigation of high-energy hadronic interactions, KASCADE [9] follows the concept of a multi-detector set-up to provide as much as possible redundant information for each single air-shower event. The multidetector system allows to measure the total electron ($E_e > 5\,\mathrm{MeV}$) and muon numbers ($E_\mu > 240\,\mathrm{MeV}$) of the shower separately using an array of 252 detector stations in a grid of $200 \times 200\,\mathrm{m}$. Additionally muon densities at three further muon energy thresholds and the hadronic core of the shower by a $300\,\mathrm{m}^2$ iron sampling calorimeter are measured.

The basic analysis of KASCADE to obtain the energy and mass of the cosmic rays is a procedure of unfolding the two-dimensional electron-muon number spectrum (Fig. 2) into the energy spectra of five primary mass groups [10]. The problem can be considered as a system of coupled Fredholm

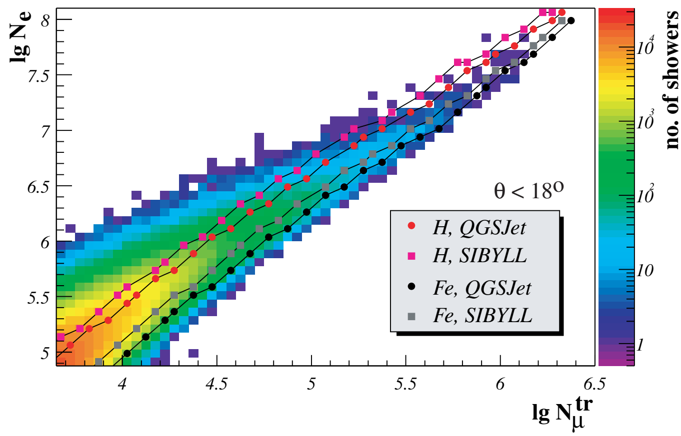

Fig. 2. Two dimensional electron (N_e) and muon ($N_\mu^{\rm tr}$) number spectrum measured by the KASCADE array. Lines display the most probable values for proton and iron simulations of two different hadronic interaction models.

integral equations of the form

$$\frac{dJ}{d\ \lg N_e d\ \lg N_\mu^{\rm tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{d\,J_A}{d\ \lg E} \times p_A(\lg N_e\,,\ \lg N_\mu^{\rm tr}\ \mid\ \lg E) d\ \lg E\,,$$

where the probability p_A is a further integral with a kernel function factorized into three parts, describing *(i)* the shower fluctuations, *i.e.* the distribution of electron and muon numbers for fixed primary energy and mass; *(ii)* the trigger efficiency of the experiment; *(iii)* the reconstruction probabilities, *i.e.* the distributions of reconstructed N_e and $N_\mu^{\rm tr}$ for given true numbers of electrons and muons. The probabilities p_A are obtained by extensive Monte Carlo simulations partly followed by a detailed detector simulation based on GEANT. The application of the unfolding procedure to the data is performed on basis of two different hadronic interaction models (QGSJet [11] and SIBYLL [12]) as options embedded in CORSIKA [13] for the reconstruction of the kernel functions. Fig. 2 displays the mean distributions of the generated showers in the electron-muon number plane for both interaction models and for proton and iron primaries. Obviously the differences for both model leads to differences of the results of the unfolding procedure, as seen in Fig. 3.

It is worthwhile to note that despite of the large differences in the relative abundances of the primary mass groups, the all-particle energy spectrum and the fact that the knee is caused by the decreasing flux of light primaries, are very similar for both models. Results of further tests using different data sets, different unfolding methods, *etc.* show the same behavior [14].

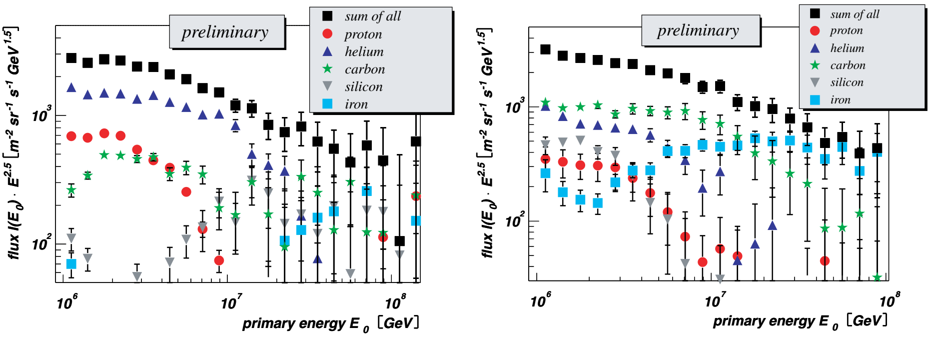

Fig. 3. Results of the unfolding procedure. Left panel: analyses based on QGSJet; right panel: based on SIBYLL.

None of the present hadronic interaction models can describe our multidimensional data consistently. Nevertheless there is, together with correlation information of the parameters used for model tests, no need to introduce a general new feature of the hadronic interactions, to account for our data.

The finding of the knee caused by light primaries is corroborated by results of an analysis of muon density measurements at KASCADE [15], which were performed independently of the present reconstructions. With a much smaller influence of Monte Carlo simulations it could be shown, that data samples with enhanced light primaries show a knee feature, whereas samples with enhanced heavy primaries do not show so up to 10 PeV.
The air-shower events registered by KASCADE were additionally analyzed in terms of large scale anisotropies and point source signals. Within the statistical limits no deviation from a global isotropy of the arrival directions could be found [16], but the statistical sensitivity of KASCADE is not high enough to confirm or disproof the predictions of Candia *et al.* [5].

There is also no positive evidence from KASCADE for primary photons in the PeV energy range [17], but the upper limits on the galactic diffuse gamma ray flux could be noticeably improved as compared to other experiments.

The astrophysical results so far available from KASCADE can be summarized as: The knee in the PeV range is caused by the decrease of the flux of light particles, and heavier (A>20) primary particles exhibit no knee up to 10 PeV. This leads to an increase of the mean mass of cosmic rays when passing the knee region in energy. Due to the present uncertainties of the hadronic interactions in the atmosphere (*e.g.* the high-energy extrapolations, the diffraction cross-section and multiplicity parametrisations of the models) it is presently not possible to give more refined quantitative results.

4. The position of the proton knee

The most abundant particles in the TeV range of cosmic rays are protons. Hence there is a high interest in the proton spectrum in the range of the crossover from direct to air-shower measurements, especially in view of various theories predicting different positions of the proton knee, depending on the magnetic field strength and size of the acceleration or diffusion region.

Some of the direct measurements favor a proton knee at 10 TeV [18], recent results from the Tibet air-shower experiment (sensitive to lower energies than KASCADE due to the larger observation height of 4300 m) claim the proton knee at around 500 TeV [19], whereas KASCADE observes a change of the spectrum at 3–5 PeV [10]. Measurements of a more detailed structure of the proton spectrum therefore are of astrophysical importance. But due to different measurement techniques they are difficult to compare. To establish a more comprehensive picture of the proton spectrum from 1 TeV to 100 PeV is one of the main tasks of future cosmic ray experiments.

5. Charged cosmic rays and TeV gamma ray astronomy

Supernova shock acceleration is believed to be the main source of the cosmic rays in our galaxy. But positive evidence for proton acceleration at these kind of objects is still missing. If protons are accelerated to PeV energies some of them should interact with the surrounding matter producing π^0 which decay into high-energy gammas in the TeV range.

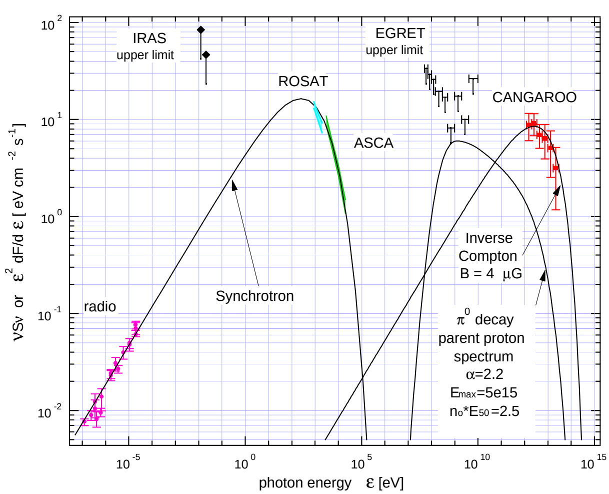

Fig. 4. Multi-band spectrum of energy fluxes from SN1006 by different experiments. Solid lines are fits to models of inverse Compton gamma production and pion decay production, respectively (from [21]).

In the last decade there has been a lot of progress in TeV-gamma ray astronomy [20], and indeed supernova remnants were found as sources of TeV-gammas. But by comparing the spectra with measurements at lower frequency bands, the TeV gamma ray fluxes can be consistently explained by a 'self-synchrotron–inverse-Compton' model, *i.e.* by electron acceleration without any contribution from pion decays [21] (Fig. 4). Just recently Berezhko and Völk [22] suggested a theoretical picture of a more efficient proton acceleration inside the sources which can explain the measured spectra also with proton acceleration and a smaller contribution of inverse Compton produced gammas.

Further measurements of this kind provide interesting aspects in understanding the source of charged cosmic rays.

6. Future prospects

The investigations of charged cosmic rays around the knee will be continued and improved by the KASCADE-Grande experiment [23, 24], which is an extension of KASCADE to measure air-showers up to primary energies of 1 EeV. KASCADE-Grande is also an multi-detector setup, and therefore correlation analyses are able to check the validity of hadronic interaction models. This provides complementary information to the LHC measurements due to the extreme forward physics of the air-shower development.

Concerning direct measurements new technical issues may allow to fly larger detectors during longer flights, which would increase the statistical accuracy at higher energies. Also new TeV-gamma ray experiments with higher sensitivity presently under construction will contribute to solve the puzzle of source, acceleration, and transport of high energy cosmic rays, and in particular the origin of the knee.

REFERENCES

[1] A. Haungs, H. Rebel, M. Roth, *Rep. Prog. Phys.* **66**, 1145 (2003).
[2] R. Engel, H. Rebel, *Acta Phys. Pol. B* **35**, 321 (2004), these proceedings.
[3] J. Milke *et al.* [KASCADE coll.], *Acta Phys. Pol. B*, **35**, 341 (2004), these proceedings.
[4] P.L. Biermann *et al.*, preprint `astro-ph/0302201`.
[5] J. Candia *et al.*, *J. Cosmol. Astropart. Phys.* **05**, 3 (2003).
[6] D. Kazanas, A. Nikolaidis, *Gen. Relativ. Gravitation* **35**, 1117 (2001).
[7] R. Wigmans, *Astrop. Phys.* **19**, 379 (2003).
[8] see `url: http://www-ik.fzk.de/~needs/`
[9] T. Antoni *et al.* [KASCADE coll.], *Nucl. Instrum. Methods A* **513**, 429 (2003).

[10] H. Ulrich *et al.* [KASCADE coll.], *Nucl. Phys. B (Proc. Suppl.)* **122**, 218 (2003).

[11] N.N. Kalmykov, S.S. Ostapchenko, *Yad. Fiz.* **56**, 105 (1993).

[12] R. Engel *et al.*, 26$^{\rm th}$ICRC (Salt Lake City) 1, 415 (1999).

[13] D. Heck *et al.*, Report FZKA 6019, Forschungszentrum Karlsruhe (1998).

[14] M. Roth, H. Ulrich *et al.* [KASCADE coll.], 28$^{\rm th}$ICRC (Tsukuba) 1, 131 (2003).

[15] T. Antoni *et al.* [KASCADE coll.], *Astropart. Phys.* **16**, 373 (2002).

[16] G. Maier *et al.* [KASCADE coll.], 28$^{\rm th}$ICRC (Tsukuba) 1, 179 (2003).

[17] G. Schatz, F. Feßler *et al.* [KASCADE coll.], 28$^{\rm th}$ICRC (Tsukuba) 4, 2293 (2003).

[18] V.I. Zatsepin *et al.*, 23$^{\rm rd}$ICRC (Calgary) 2, 13 (1993).

[19] M. Amenomori *et al.*, *Phys. Rev.* **D62**, 112002 (2000).

[20] R. Ong, *Phys. Rep.* **305**, 93 (1998).

[21] T. Tanimori *et al.*, 27$^{\rm th}$ICRC (Hamburg) **6**, 2465 (2001).

[22] E.G. Berezhko, L.T. Ksenofontov, H. Völk, *Astron. Astrophys.* **395**, 943 (2002).

[23] A. Haungs *et al.* [KASCADE-Grande coll.], 28$^{\rm th}$ICRC (Tsukuba) 2, 985 (2003).

[24] K-H. Kampert *et al.* [KASCADE-Grande coll.], *Nucl. Phys. B (Proc. Suppl.)* **122**, 422 (2003).