EAS EXPERIMENTS SOLVING KNEE PROBLEM

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June 14, 2004

Why it is important

A new paradigm in astrophysics research consists in the detection of celestial objects in radio, optical, X, and gamma rays**.** A variety of compatible measurements give sufficient enough information for building realistic models of physical processes of supernovae explosions, of accompanying gamma-ray bursts, of accretion disc interactions with super-dense objects, and finally of the evolution of the Universe itself. In this case additional information about the particles of highest energies arriving to Solar system will significantly enlarge the information on the most violent processes in the Universe.

What they are

Cosmic Ray (CR) flux incident on terrestrial atmosphere consists mostly of protons and heavier stripped nuclei accelerated at numerous galactic and extragalactic sites.
The most exciting question associated with cosmic rays is the exploration of a particular astrophysical accelerating source. Due to the bending in galactic magnetic fields, charged particles loose information about the parent sites during long travel and arrive to Earth highly isotropic. Galactic cosmic rays cannot map the objects where they born, therefore, only integrated information from all sources are available from measurements of cosmic ray fluxes near Earth and on the Earth's surface. This information consists of the shape of the energy spectra of the different species of cosmic rays, and of the anisotropy of the CR arrival (Chilingarian, 2003).
The energy spectrum is of non-thermal origin and follows a power law $dN/dE \approx E^{\gamma}$ over many orders of magnitude. The spectrum steepens at energies around 4 PeV from a spectral index $\gamma \approx -2.7$ to $\gamma \approx -3.1$. This feature is commonly called the knee and its explanation is generally believed to be a corner stone in understanding the origin of cosmic rays, providing answers to one of the key questions of astroparticle physics (Horandel, 2004).

Difficulties

Presently, above 1 PeV cosmic rays are experimentally accessible in ground-based installations only. These detectors do not measure the primary particles; instead secondary particles are measured, produced in high-energy interactions in the atmosphere, forming an extensive air shower. This makes the interpretation of the indirect measurements very difficult and the results obtained depend on the understanding of high-energy interactions in the atmosphere (Horandel, 2004).
In spite of many efforts, we have still only a rudimentary understanding of, where these particles are coming from, how they are accelerated to such extremely high energies, how they propagate through interstellar space, and in addition how they interact with matter (Haungs et al., 2003).

What we are measuring – All Particle Spectra

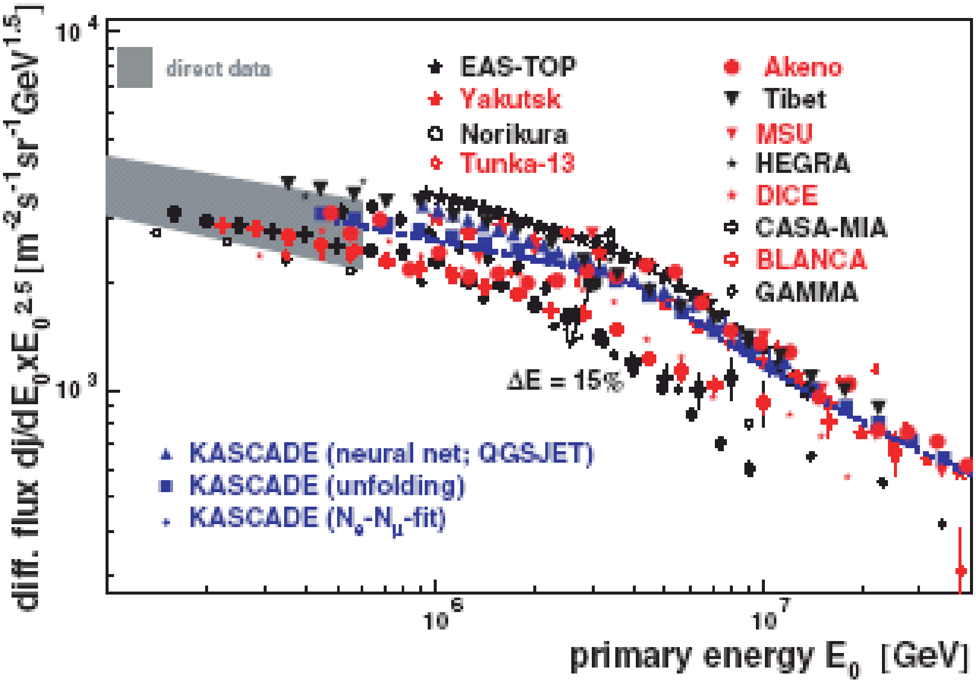

Figure 1 Compilation of different experimental results on the cosmic ray all-particle energyspectrum around the knee (from Haungs et. al, 2003). The effect of a 15% uncertainty inenergy reconstruction is indicated by 2-sided arrow.

Assuming an uncertainty of 15% for the energy reconstruction all the results presented in the Figure 1 appear to be concordant. Despite considerable differences of the applied methods analyzing the observables, different simulation procedures, and different observation levels the compiled experimental results agree remarkably. Only at the high-energy end do the spectra exhibit larger differences, maybe as a consequence of saturation effects of the different detector devices, in addition to missing statistical accuracy and also due to larger uncertainties of the models providing the reference patterns. This observation is remarkable, in particular as most of the experimental results have been published without quoting systematic uncertainties arising from the reconstruction procedures or the model dependence.

After compiling the data (14 spectra) the average values and their variances result in a slope below the knee to $\gamma 1 = -(2.68 \pm 0.06)$ and above the knee to $\gamma 2 = -(3.06 \pm 0.08)$ with the knee position at $E_k = (3.2 \pm 1.2) \times 10^{15}$ eV, without taking into account the statistical accuracy of the different experiments or any further systematic uncertainty of the given results. In most cases systematic uncertainties are not communicated for the results shown in the plot.

Why all particle specter isn't sufficient for definite physical inference on origin of Knee

Table Theoretical models of the Knee (from Hoerandel, 2004)

Model	Author(s)
Source/Acceleration:	
Acceleration in SNR	Berezhko & Ksenofontov [18]
Acceleration in SNR + radio galaxies	Stanev et al. [19]
Acceleration by oblique shocks	Kobayakawa et al. [20]
Acceleration in variety of SNR	Sveshnikova [21]
Single source model	Erlykin & Wolfendale [22]
Reacceleration in the galactic wind	V¨olk and Zirakashvili [23]
Cannonball model	Plaga [24]
Propagation/Leakage from Galaxy:	
Minimum pathlength model	Swordy [25]
Anomalous diffusion model	Lagutin et al. [26]
Hall diffusion model	Ptuskin et al. [27], Kalmykov & Pavlov [42]
Diffusion in turbulent magnetic fields	Ogio and Kakimoto [28]
Diffusion and drift	Roulet et al [29]
Interactions with background particles:	
Diffusion model + photo-disintegration	Tkaczyk [30]
Interaction with neutrinos in galactic halo	Dova et al. [31]
Photo-disintegration (optical and UV photons)	Candia et al. [32]
New interactions in the atmosphere:	
Gravitons, SUSY, technicolor	Kazanas & Nicolaidis [33, 34]

Most of 17 models from the Table yield similar all-particle spectra. On the other hand, the predictions on the behavior of the individual element spectra are quite different.

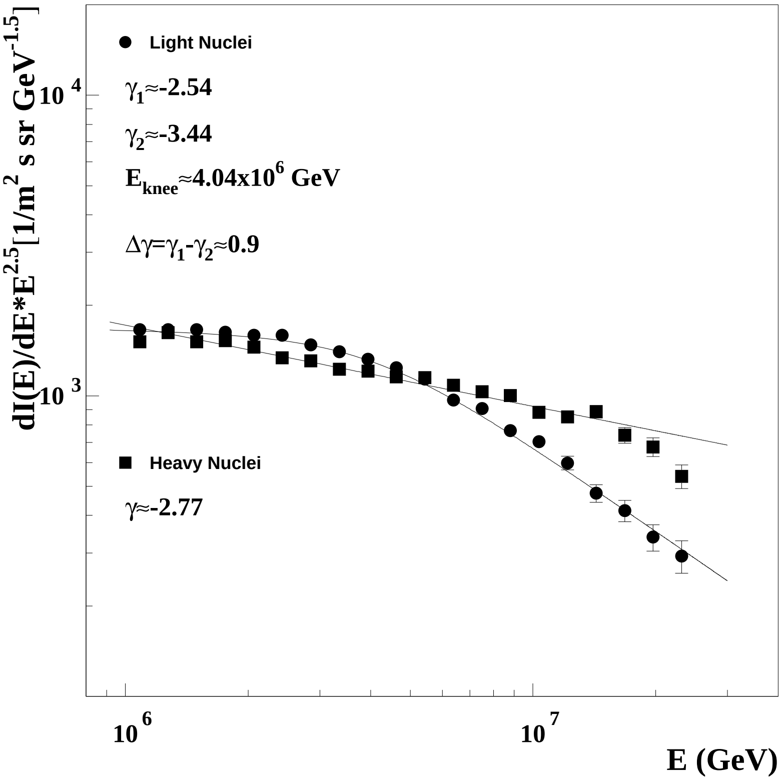

Figure 2 Energy spectra of light and heavy nuclei obtained by neural classification and energy estimation. EAS characteristics used : Shower Size and Shape (Age), from Chilingarian et.al., 2004.

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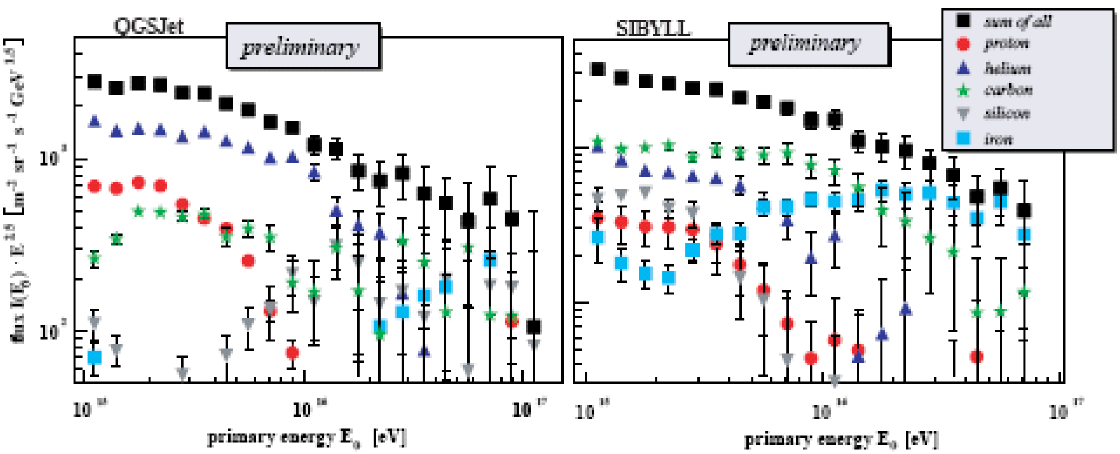

Figure 3 Results of the unfolding procedure using QGSJET (left) and SIBYLL (right), from (Kampert et al., 2004)

The result of the unfolding is presented in Figure 3 for two interaction models used in KASCADE experiment (Antoni et al., 2003b). The all-particle spectra agree very well and in both cases the knee is caused by the decreasing flux of the light primaries, demonstrated very sharp knee feature. Tests using different data sets, different unfolding methods, etc. show the same behavior.

The available world data also confirms existence of very sharp knee for the CR light component. I Figure 4 we present the world data on the light mass group spectra. Energy spectra of KASCADE (Vardanyan et.al., 1999) and MAKET-ANI (Chilingarian, et.al., 2004),experiments are in good agreement in terms of intensities, shape of the spectra and spectral indices. HEGRA spectrum, obtained with completely different experimental methodic, also prove steepening of the light mass group spectra and shift of the knee position to the lower values of primary energy comparing with all-particle spectra.

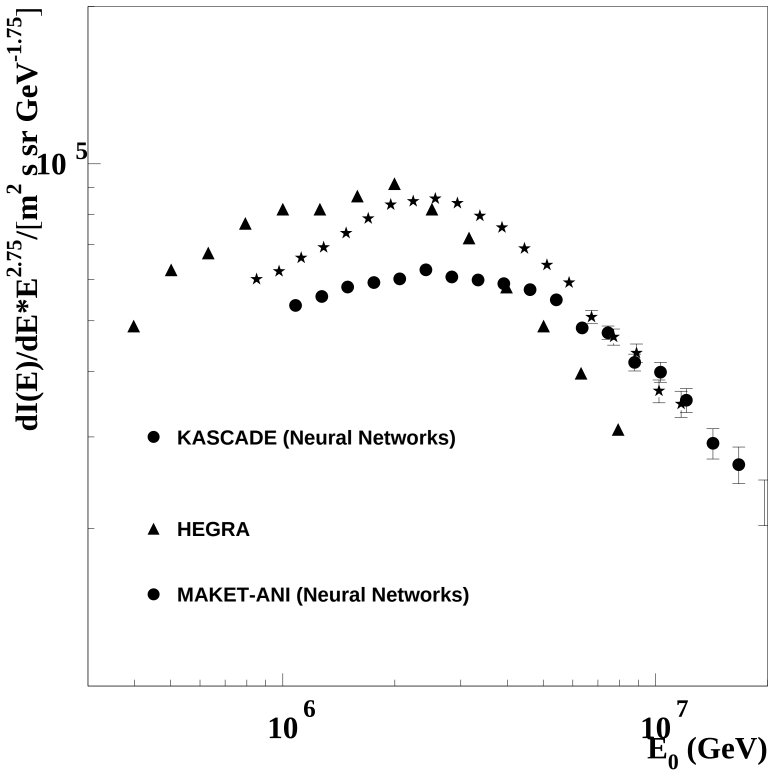

Figure 4 4 Light group spectra (world survey) (Arqueros et.al.,2000, Vardanyan et.al., 1999, Chilingarian et.al., 2004)

Conclusions

- KASCADE has provided a wealth of new high quality EAS data in the knee region giving important insight into the origin of the knee and of CRs in general. Conclusive evidence has been reached on the knee being caused by light primaries mostly. Furthermore, the data are in agreement with a rigidity scaling of the knee position giving support to an astrophysical origin by either maximum acceleration or diffusion/drift models of propagation (Kampert et al., 2004).
- At present, the experimental results do not allow to select a single approach as the best model to describe nature. The origin of the knee in the all-particle energy spectrum is not yet explained.However, within the boundaries given by the experiments, acceleration in supernova remnants and diffusive propagation through the Galaxy seem to be very attractive models to understand the origin of the knee (Horandel, 2004).
- Without knowing the interactions of the unknown particles, even theenergy estimation of giant EAS and the scale of the spectrum will remain finally under debate.Nevertheless

the detailed investigations in the last decade make us quite sure that the knee at 3–5 PeV is caused by a decrease in the galactic flux of the light mass nuclei (Haungs et. al, 2003).

- The SNR acceleration model is supported by the MAKET-ANI data on partial energy spectra; our conclusions on rigidity dependant acceleration are consistent with the evidence we saw recently about how the solar accelerators work. The recently proposed mechanisms of particle acceleration in the SN1006 (Berezhko et al., 2003) is consistent with the mechanisms of solar particle acceleration by CME driven shocks, of course, at much lower particle energy scales (Chilingarian, 2003).

Energy spectra of primary ions from Z=1 to Z=26 contains valuable information on the knee origin. Unfortunately information contain of the EAS experiments does not provide enough clues for such "spectroscopy" of the "knee region". Nevertheless, precise measurements of the electron and muon content, and implementation of the CORSIKA simulation code by the KASCADE experiment (Heck et al., 1998) as was demonstrated in numerous papers (see for example (Chilingarian et al., 1999a), (Antoni et al., 2003a)), allows the classification of primaries according to 3 classes: "light", "intermediate" and "heavy". Implementation of the nonparametric multivariate methodology of data analysis ((Chilingarian, 1989), allows the event-by-event-analysis of EAS data (Chilingarian et al., 1991), using Bayesian and Neural Network information technologies (Chilingarian , 1994, 1995), (Bishop, 1995). At each stage of the analysis we estimate the value of the information content of the variables used for EAS classification and energy estimation and restrict the complexity of the physical inference according to this value. The MAKET-ANI experiment is located at 3200 m. above sea level on Mt. Aragats, In Armenia; the quality of reconstruction of the EAS size and shape are good enough and we can use them for the EAS classification shower size and shape parameters (the so called shower age). The distinctive information contained in distributions of these parameters allows us to classify the EAS with high level of accuracy into two distinct groups: initiated by "light" or ""heavy" nucleolus. In the KASCDE experiment (Antoni et al., 2003b), where the muon content of the EAS is measured in addition to shower electron size, and we can classify showers into 3 categories adding also the "intermediate" class.
The differences of the spectra slope before and after the knee for different mass groups of the primary cosmic ray flux is the key feature for the solving of the Knee origin problem. Most important issues of the running EAS experiments is selection of the showers induced by the same primary group, and not – by the primaries of same energy as proposed in (Daryan et al., 2001, Garyaka A.P., Martirosov R.M. et.al., 2002).
Two recent papers again illustrate importance of new approaches in physics of the knee region. In (Anglietta et al., 2004), the light mass group was isolated using information on the EAS electrons and TeV muons. Obtained knee position at $E_k \approx 4 \cdot 10^{15}$ eV and difference of the slopes after and before the knee for light component equals to $\gamma_2 - \gamma_1 = 0.7 \pm 0.3$ *, as compared with all charged particles spectra* $\gamma_2 - \gamma_1 = 0.4 \pm 0.1$ again can be interpreted in the standard framework of rigidity dependent acceleration/ propagation processes.
Another illustration of the soundness of the idea of importance of the single source of CR is theoretical work of (Wick et al., 2004), introducing estimation of the possible influence of the nearest Gamma Ray Burst on the Cr intensity in the vicinity of Earth. Obtained partial spectra after fitting of the model parameters coincide rather well with sharply changing after the knee KASCADE light component spectra.

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