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WHAT DO WE EXPECT TO LEARN FROM VERY HIGH ENERGY COSMIC RAY OBSERVATIONS?*

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By a short tour through the exciting field of very high-energy and ultra high-energy cosmic rays studies, a brief review is given about the current questions approached, in particular by the KASCADE experiment and the Pierre Auger project. The present status of the investigations of the knee region of the cosmic ray spectrum by KASCADE is presented and open problems are discussed.

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1. Introduction

Many kinds of radiation exist in the Universe, electromagnetic radiation and particles with a broad range of wavelengths and energies, respectively. Some of the radiation is produced in stars and galaxies, while some is the cosmological background radiation, a relic from the cosmic evolution. Among this radiation, the most energetic are cosmic rays particles, dominantly protons, helium, carbon, nitrogen up to iron ions in a appreciable amount.

They continuously bombard our Earth from the cosmos by an isotropic stream of high energy particles. These cosmic rays were discovered in 1912 by the Austrian Victor Hess (see [1]) through a series of balloon flights, in which he carried electrometers to over 5000 m altitudes. Nowadays we know that the energy spectrum of these particles extends from 1 GeV to beyond 10^{20} eV (100 EeV), to the highest energies of known individual particles in the Universe. However, we have only a rudimentary understanding, where these particles are coming from, how they are accelerated to such high energies and how they propagate through the interstellar space. The difficulty is that cosmic rays are overwhelmingly charged particles (stripped nuclei), and

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the galactic magnetic fields are sufficiently strong to scramble their paths. Perhaps, except at highest energies cosmic rays have lost all their memory about the location of the emission sources, when they eventually arrive at the Earth's atmosphere. Hence the only observable quantities, which may give us some information are *the energy distribution* and *the elemental composition* of primary cosmic rays, at highest energies eventually with *deviations from isotropic incidence*. The experimental determination of such quantities are topics of contemporary research, especially in regions which exceed the energies provided by man-made accelerators.

The following brief overview will give an impression about the current experimental activities with their astrophysical motivations.

The rather featureless energy spectrum of primary cosmic rays (Fig. 1) comprises more than 12 orders of magnitude in the energy scale. It follows an overall power-law ($\propto E^{-2.7}$: note that the flux is multiplied by $E^{2.7}$) with a distinct change around 10^{15} eV, called the *"knee"*. This feature, still not consistently explained, has been discovered 40 years ago by Kulikov and Khristiansen from the Moscow State University [2] with studies of the intensity spectrum of Extensive Air Showers (EAS), of the so-called shower size, which roughly reflects the primary energy. The flux of primary cosmic rays falls from 1 particle/m^2 s to 1 particle/km^2 century at highest energies. A great deal of interest and current efforts concern the shape of the spectrum in the *E*eV-region, above 10^{18} eV, where the spectrum seems to flatten ("ankle"), especially around 5×10^{19} eV, with the theoretically pre-

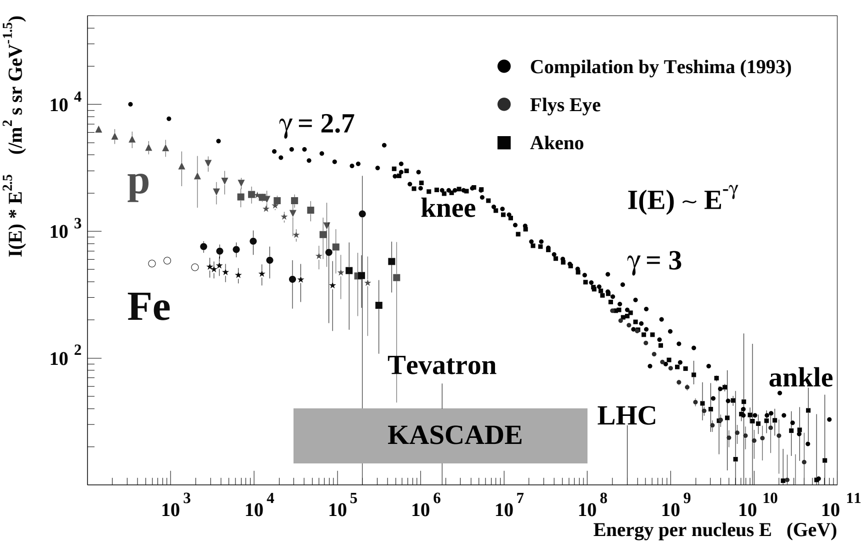

Fig. 1. Primary energy spectrum of cosmic rays.

dicted Greisen–Zazepin–Kuzmin cut-off [3], due to the photo-interaction of protons with the 2.7 K-background radiation. The AGASA experiment in Akeno (Japan) [4], in particular, has shown that this limit does not exist, and this fact is an issue of extreme astrophysical and cosmological relevance, establishing an enigma.

Below 10^{14} eV the flux of particles is sufficiently large for individual nuclei to be studied by flying detectors in balloons and satellites. From such *direct* experiments we know that the majority of particles are nuclei of common elements. Around 1 GeV the abundances are strikingly similar to those found in ordinary material of the solar system. Striking exceptions are the abundance of elements like Li, Be, and B, overabundant since originating from spallation of heavier nuclei in the interstellar medium.

2. Methodical features and techniques

Above 10^{14} eV the techniques used to study cosmic rays employ the phenomenon of extensive air showers discovered independently by Auger *et al.* [5] and Kohlhörster *et al.* [6] in 1938.

Most of the produced particles in the hadronic interactions are pions and kaons, which can decay into muons and neutrinos before interacting, thus producing the most penetrating component of atmospheric showers. The most intensive component, electrons and photons, originates from the fast decay of neutral pions into photons, which initiate electromagnetic showers, thus distributing the originally high energy over millions of charged particles. The backbone of an air shower is the hadronic component of nucleons, pions and more exotic particles (Fig. 2).

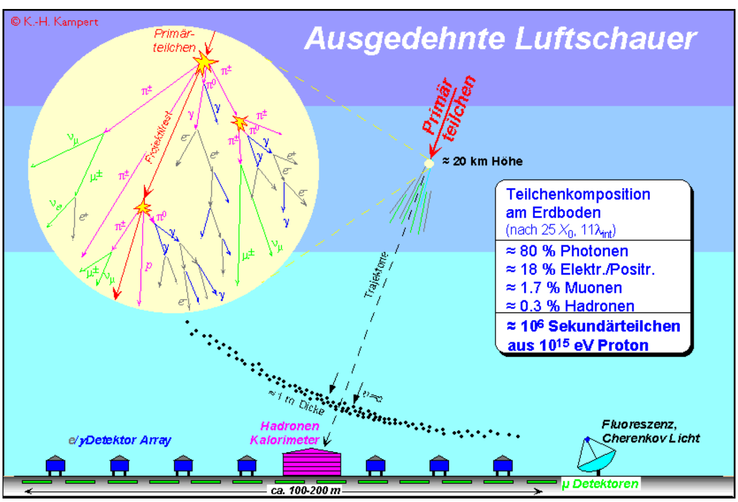

Fig. 2. Extensive air showers — Ausgedehnte Luftschauer — Grandes gerbes.

The electromagnetic component is accompanied by an additional EAS phenomenon, the production of atmospheric Cerenkov light which carries further information about the shower development. For EAS with higher energies ($> 10^{17}$ eV) also the nitrogen fluorescence light induced in the atmosphere can be observed.

However, in ground based experiments, in general, we are not in the situation to see the longitudinal development, we observe only the developed status of the air shower cascade at a certain observation level. From the observables, that means from *the intensity, the lateral and eventually the energy distributions*, we have to deduce the properties of the primary particle.

The intensity and the width of the lateral distributions of the three components are very different. The muons, for example, extend to several hundred meters as most of them are produced very high in the atmosphere. Therefore, even a small transverse momentum imparted to them in the production can lead to large distances from the shower axis.

In an EAS experiment the lateral distributions of the particles are sampled by more or less regular arrangements of a large number of detectors which cover only a small fraction of the total area. This sampling is an additional source of fluctuations which add to the large spread resulting from the inherent statistical fluctuations of the shower development in the atmosphere. As an example the photo shows the KASCADE [7] detector arrangement, installed in Forschungszentrum Karlsruhe.

KASCADE (Fig. 3) is a multi-component detector array: a field of electron–muon counters and a central detector set-up, which is a complex arrangement of several types of detectors, basically a iron sampling calorimeter for hadron measurements and multiwire proportional chambers below, for studies of the higher energy muon component, and other detectors for special purposes.

Fig. 3. KASCADE detector array with a field array, a central detector for measuring the hadron component and the muon component at various energy thresholds. In addition there is a muon tracking detector arrangement in a tunnel.

I would like to mention that the KASCADE collaboration is just extending the detector, together with the University of Torino, in order to register efficiently showers at energies up to beyond the LHC energy: KASCADE GRANDE [8] distributes the detector stations over an $800 \times 700\,\mathrm{m}^2$ area.

The general scheme of inference in a modern EAS experiment is displayed in Fig. 4, indicating also the involved difficulties.

The identification of differences in EAS which result from differences in mass of the primary particle requires a modelling of shower development in the atmosphere. For that Monte Carlo programs of the EAS develop-

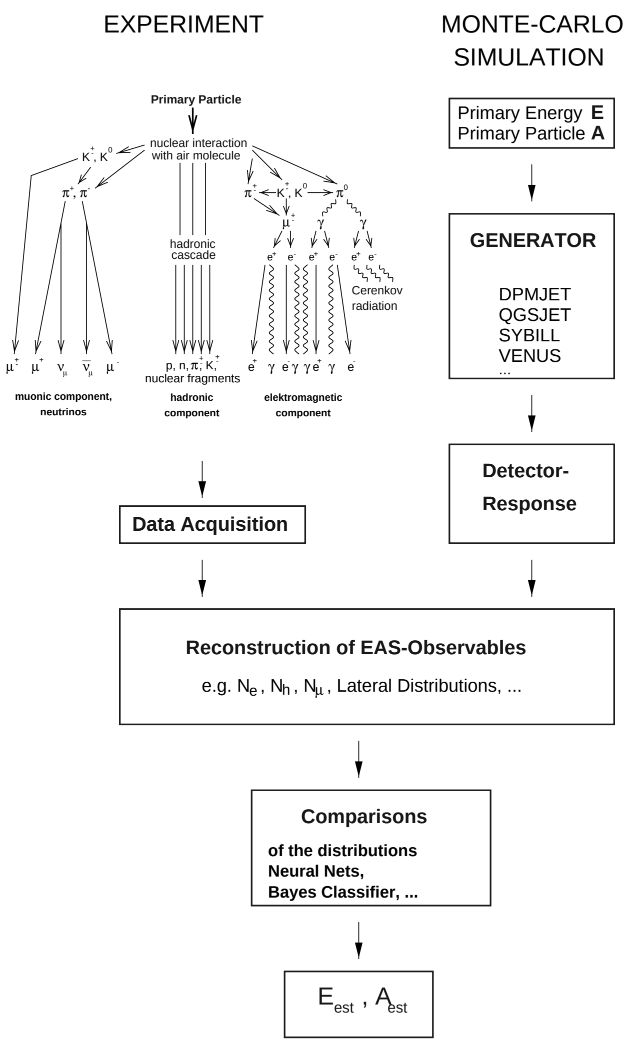

Fig. 4. General scheme of the analysis of EAS observations.

ment like the Karlsruhe CORSIKA program have been developed [9]. It is under continuous modification and improvement. A prerequisite for the Monte Carlo procedures is a knowledge about particle production in high-energy hadronic interactions. Since the energy region of our interest exceeds the particle energies provided at man made accelerators, we rely on model descriptions which extend the present knowledge to a *terra incognita*, on basis of more or less detailed theoretical approaches of phenomenological nature and with QCD inspired ideas. (The development of such models is an item of its own.) The CORSIKA code includes various models, presently *en vogue* as options, and in fact, the model dependence is an obvious feature in the actual comparisons with the experimental data.

A multi-detector experiment observing simultaneously all major EAS components with many observables provides some possibilities to test the hadronic interaction models and to specify the most consistent one.

The stochastic character of the huge number of cascading interactions in the shower development implies considerable fluctuations of the experimentally observed EAS parameters and of the corresponding simulated showers as well, clouding the properties of the original particle. The inherent (unavoidable) fluctuations establish an important and intriguing difficulty of the EAS analysis and need adequate response of the analysis methods.

The further processing is to compare real data with pseudo experimental data on equal level, including the detector response and expressed by various reconstructed shower variables: *shower intensity, the lateral, arrival time and eventually energy distributions of the various EAS components.*

The most efficient observables with respect to the mass composition is the correlation of total intensities of the electron and muon components (showers sizes N_e and N_μ). This is obvious from the inspection of the different longitudinal development of the shower sizes (Fig. 5).

For the comparison of the observables with the pseudo data we have to realise: None of the observables is strictly only dependent on the mass of primary, or only dependent from the energy, and since we are investigating an *a priori* unknown spectral distribution accompanied by another *a priori* unknown variation of the elemental composition (or *vice versa*), there is always an intriguing feedback of the estimates of both. Therefore, multivariate analyses, correlating the observations of different EAS variables are strongly required, and the inference from only one EAS component has been often misleading. For the analysis of the correlated distributions without any bias of a constraining parameterisation, there are adequate methods worked out involving neural networks and Bayesian decision making [10,11]. Applying these techniques, for each particular case, *i.e.* for a particular set of selected EAS variables or for a chosen number of mass groups or for

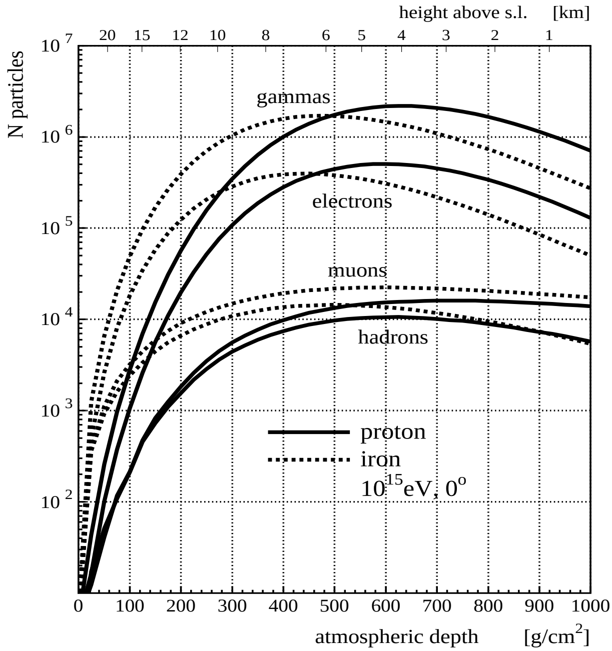

Fig. 5. Longitudinal EAS development.

a specific hadronic interaction model generating the reference patterns, matrices for true and misclassification are obtained. From that measures for the confidence and errors can be constructed.

3. The knee

It is currently believed that cosmic rays are accelerated in a process called diffusive shock acceleration. Suitable astrophysical shocks occur in supernova explosions and the particles of the interstellar medium gain energy as they are repeatedly overtaken by the expanding shock wave. Such a mechanism leads in fact to a power law spectrum with the maximum energy of about $Z \times 10^{14}$ eV [12]. The upper limit $E_{\max} \propto Z(\boldsymbol{r} \times \boldsymbol{B})$ reflect the dependence from the size and the magnetic field of the accelerator region. Alternatively the knee has been qualitatively explained by the leaky box model that the galactic magnetic field let escape first the protons due to their larger stiffness at the same energy compared to Fe. In order to constrain the models and conjectures a better knowledge of the shape of energy spectrum around the knee is quite important. In particular, all approaches accounting for the origin and acceleration mechanism, imply specific variation of the elemental composition of primary cosmic rays, sometimes in a very detailed manner. That are the issues addressed by the KASCADE experiment set up in Forschungszentrum Karlsruhe.

The concept of the KASCADE experiment with a multi-component detector array is to measure a larger number of EAS variables for each individual event with high accuracy. For this aim the detector has been designed. Specific EAS variables accessible, in addition to the shower size N_e and the truncated muon number N_μ^{tr}, are the number of hadrons N_h^{100} with energies larger than 100 GeV, the energy sum $\sum E_h$ of these hadrons, the energy of the most energetic hadrons E_h^{max}, the number N_μ^* of muons with energies larger than 2 GeV and others like some quantities representing the muon arrival time distribution.

Fig. 6 presents two solutions with the same data and the same analysis procedures, but based on reference patterns from different hadronic interaction models. This indicates the present limits due to the unavoidable model dependence of any analysis.

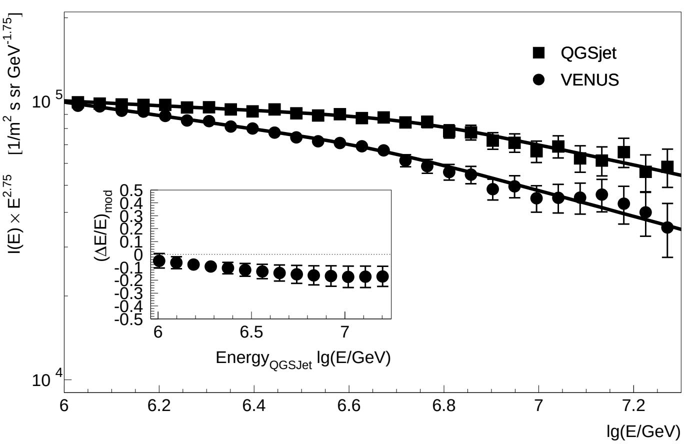

Fig. 6. The primary energy spectrum around the knee resulting from KASCADE data analyses on basis of two different hadronic interaction models [13,11].

Furthermore the result (we have much confidence in the QGSJet result) should be seen under various aspects of current controversial discussions: Is there an abrupt break in the spectrum (how the Akeno observations claim) and where it is located? Or, is the change of the spectral index rather smooth as seemingly observed in the high altitude Tibet array (4300 m a.s.l.)?

Some years ago a hypothesis about origin of cosmic rays around the knee, a theory propagated by Erlykin and Wolfendale [14], predicted a modulation in the energy spectrum, wiggles due to the various mass production spectra of a single supernova explosion, localised only few hundred light years away from our solar system. Our data do not support this conjecture.

What concerns the mass composition, in the moment we may characterise the situation by the energy spectra of various mass groups (Fig. 7) resulting from a non-parametric analysis *i.e.* by the most unbiased KASCADE

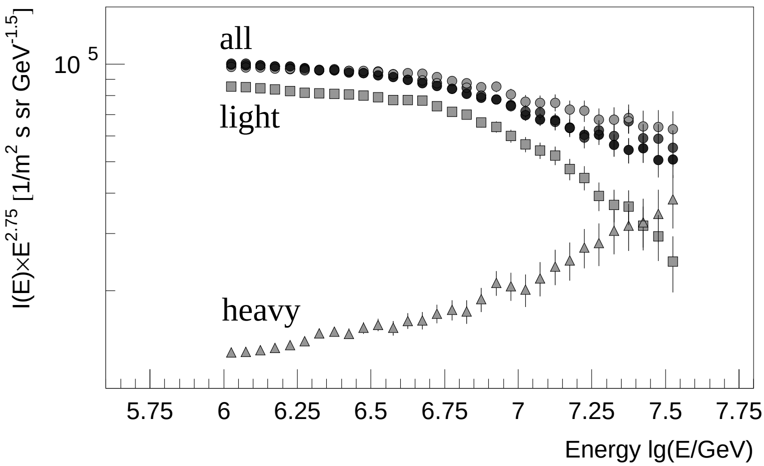

Fig. 7. Energy spectra of various mass groups [13].

result [13,11] with the feature: The knee is made by the proton component only, and with the question: Where is the iron knee? That is the focus of KASCADE GRANDE [8].

Figs. 6 and 7 display the present messages from KASCADE, analysed various times with samples of large statistics and also with different methods, in addition to nonparametric methods also with efficient parameterisations [15].

Fig. 8 displays detail examples of the reconstructed chemical composition represented by the mean mass *versus* energy identifier $\mathrm{N}_\mu^{\mathrm{tr}}$ (the knee is at $\log \mathrm{N}_\mu^{\mathrm{tr}} = 4.1$) taking into account different sets of EAS observables. The results based on the hadronic interaction model QGSJet [16] are compared. We recognise the tendency that the lighter composition before the knee get heavier beyond. The QGSJet model leads generally to a heavier composition as compared to result of the VENUS [17] model. The reconstructed mean mass depends obviously also from the correlation taken into account. This result of a feasibility study, implying a test of the used interaction model, points to the way, how the data can be consistently analysed on event by event basis with explorations of the particular sensitivities and uncertainties, from the model dependence, *e.g.* the focal points of studies around the knee can be summarised by the items:

- The detailed shape of the energy spectrum
  Smooth, with modulations or a sharp knee?
  Variation of the elemental composition
  Where is the knee of the iron component? Does it scale with Z or A?

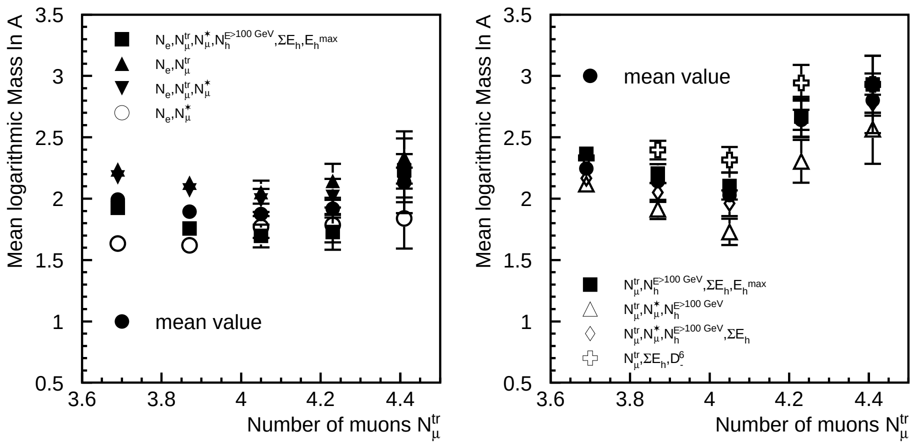

Fig. 8. Variation of the mass composition $\langle \ln A \rangle$ inferred from KASCADE data analysing various combinations of EAS observables [13].

- Test of models of the production mechanisms
- The hadronic interaction in the *terra incognita*: $> 10^{15}$ eV

I emphasise again the basic dilemma of the present status. The analyses of the measured data lead to results distinctly dependent on the particular adopted high-energy interaction model. Though, in contrast to other current experiments, the KASCADE experiment is able to specify the inherent model dependence, thanks to the large number of observables, studied simultaneously event per event, any progress needs an improved knowledge of the interaction model.

4. The ankle and above

In the range of the highest energies the first remarkable feature, in fact establishing an enigma, stems from the existence of radiation fields which fill the Universe. The 2.7 K microwave background is the best known. Above some thresholds the cosmic ray particles coming from long distances inelastically interact with those background photons. High-energy incident protons for which the background is blue shifted, start photo–pion production above a few tens of EeV and get cooled down in this way: $p + \gamma\,(3\text{K}) \rightarrow \Delta(1232) \rightarrow p + \pi^0 (n + \pi^+)$. That is the predicted Greisen–Zatsepin–Kuzmin (GZK) spectral cut-off [3]. The consequence of the interaction with the radiation fields is that above 5×10^{19} eV, photons, protons and nuclei have rather short attenuation lengths, in the order of, say several tens Mpc, and the Universe gets relatively opaque for them. To state this more explicitly:

It is impossible for ultrahigh energy cosmic particles to reach us from sources whose distance would exceed 100 Mpc (this is roughly the size of our local supercluster), unless rather exotic particles or interaction mechanisms are envisaged.

A second feature is related to the chemical composition of ultrahigh energy primary cosmic rays. If the highest energy cosmic rays would be mainly protons, as some experimental results are tentatively interpreted, the trajectories of single charged ultrahigh energy particles through the galactic and extra-galactic magnetic fields (which are believed to be of the order of μG and nG, respectively) get no more noticeably deflected over distances limited by the Greisen–Zatsepin–Kuzmin cut-off. Typically the angular deviation of a 10^{20} eV proton from a source of 30 Mpc distance would be about 2 degrees. In other words, above the cut-off, the direction of incidence of such particles should roughly point to the source: Proton astronomy should become possible to some extent, defined within the box of the consequences of the cut-off. However, looking in our astrophysical surroundings, the number of objects within a distance of a few Mpc is quite limited, if such objects are even able to accelerate particles to such extremely high energies at all.

What is the experimental knowledge?

The data around the ankle and above come from a few large-aperture ground based detector arrays with two types of techniques (Table I). From

TABLE I

UHECR detectors.

Array		Location	Area	Principal Detectors
Haverah Park	[18]	England	11 km^2	Water Cerenkov tanks
Yakutsk	[19]	Russia	10 km^2	Scintillation counters Atmospheric Cerenkov detectors Muon detectors
SUGAR	[20]	Australia	60 km^2	Muon detectors
AGASA (Akeno)	[21]	Japan	100 km^2	Scintillation counters Muon detectors
Volcano Ranch	[22]	New Mexico USA	8 km^2	Scintillation counters
Fly's Eye	[23]	Utah (USA)		Air fluorescence detector
HiRes	[24]	Utah (USA)		Air fluorescence detector

historical reasons the smaller Volcano Ranch array is added because there the first air shower event with the symbolic limit of 10^{20} eV has been observed [22]. Alternatively to particle detector arrays a second technique is based on the observation of the nitrogen fluorescence induced by the ionising particles crossing the air.

Fig. 9 displays the highest energy region of the cosmic ray spectrum as observed by the AGASA detector [4]. The figures near the data points indicate the number of events and the bars show the 90% confidence level. The energy spectrum is multiplied by E^3, so that the part below 10^{18} eV becomes flat. The ankle structure becomes evident and the deviation from the cut-off predictions. There are, of course, large error bars, but the tendency is confirmed when other 13 events are included, detected by other detectors (HiRes). The statistical accuracy of the distribution in the supergalactic plane is too low to deduce any tendency.

The UHECR events constitute an enigma, when we ask: Where are the sites and what are the acceleration mechanisms being capable to impart energies of macroscopic orders (in the most energetic case of 3×10^{20} eV equivalent to 50 joules) to a microscopic particle. Many processes have been proposed, where in an astrophysical plasma large scale macroscopic motion is transferred to individual particles, for example in a turbulence and by shock waves. The crucial role plays the size of the acceleration region and

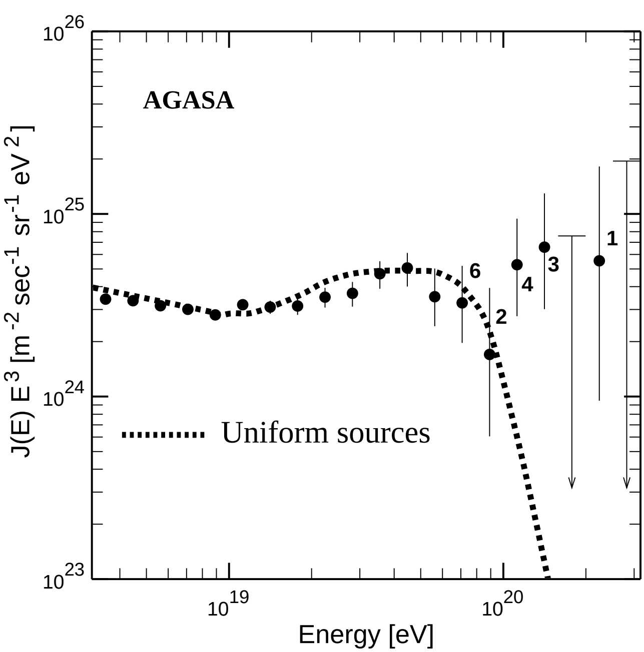

Fig. 9. Highest energy region of the cosmic ray spectrum [4].

the magnetic field embedded in the plasma and keeping the gyroradius of the particle in the acceleration region. That depends also from the velocity β of the motion. Under these aspects possible accelerator sites have scrutinised [25,26]. If all parameters related to the question are taken into account, one has to admit that none of the proposed scenarios seems fully convincing. In addition we have to keep in mind that the sources should be nearby in cosmological scales. Within the present statistical accuracy the data also do not show a distinct correlation with nearby point sources.

However, if future studies would exclude "conventional" astrophysical acceleration mechanisms, one would need to consider another class of theories proposed as possible explanation, so-called "top-down" processes (see Ref. [27]). Most of these study the possibility that UHECR arise from decay of some super-heavy X particle whose mass is in the Grand Unification range (10^{25} eV) produced during some phase transition period in the early Universe. The models differ mainly, how to produce the density of X particle to fit the UHECR observations and their survival since some 10^{-35} s after Big Bang. One should mention that such models and conjectures have quite specific features and experimental signatures (spectrum and mass composition) so that a discrimination appears to be not impossible, provided the experimental knowledge could get increased. That is just our challenge for the next generation of detectors with large apertures!

5. The next and over-next generation of detectors

The next detector is the Pierre Auger observatory with 14.000 $\mathrm{km^2 sr}$ aperture over two sites, one in each hemisphere [28].

The installation of the southern observatory (Fig. 10) has started in 2000 with a prototype array of 55 km^2 and a air fluorescence telescope, near the small town of Malargüe in the province of Mendozza, Argentina. Finally, the site will be equipped with 1600 detector stations (12 m^3 tanks filled with water detecting Cerenkov light produced by secondary particles), distributed in a grid with 1.5 km spacing. Four "eyes" composed of 30 air fluorescence telescopes will view 3000 km^2 of the site and measure during the clear moonless nights *i.e.* with a duty cycle of 10% the giant showers through the fluorescence generated in the air. By this hybrid detector a subsample of 10% of the total number of events, simultaneously observed with both techniques, makes possible a cross calibration and yield an unprecetended quality for shower identification. It is expected to detect some 50 to 100 events per year above 10^{20} eV, and 100 times more above 10^{19} eV. The Pierre Auger Project has just started, and the community looks already forward to the next generation of detectors. There is less doubt that this will be an airborne detector observing the giant shower development in the atmosphere

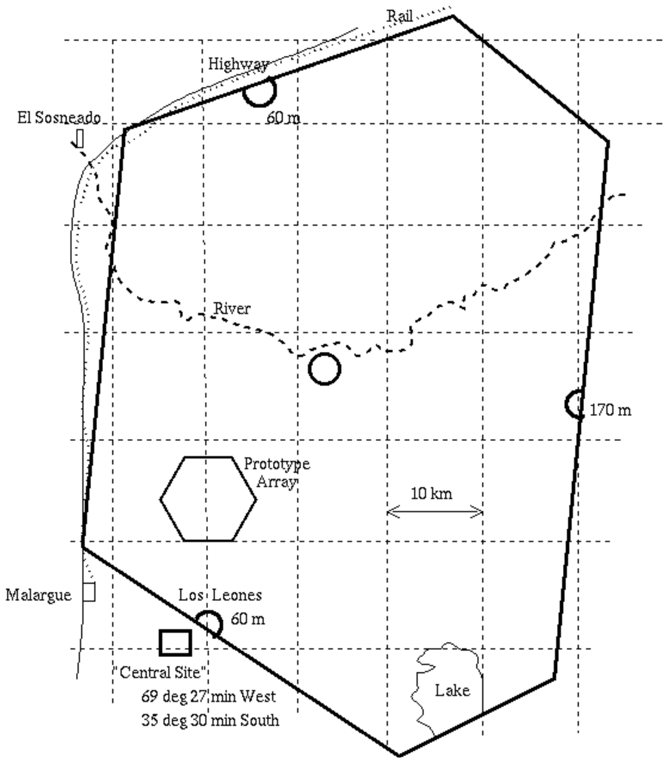

Fig. 10. Layout of the southern Pierre Auger observatory [28].

with a huge aperture quasi "from above". This is envisaged with the EUSO or Orbiting Wide Angle Light detector within the Airwatch project [29] by fluorescence detectors on satellites. This is particularly interesting when in few years it will be shown that the spectral cut-off exceeds the reach of the Pierre Auger observatory and larger statistics is necessary for studies of the focal points of Extremely High Energy Cosmic Ray Observations.
The questions are:

- What is the reason for the change of the spectral index at the ankle? A change of the production mechanism? A change of the elemental composition? Or a change of the character of the interaction?
- How is the shape of the spectrum at energies above 10^{20} eV and is there a limit of maximum energy?
- Is there any directional correlation pointing to the sources of UHCR?

With experimental answers to these questions we may provide some hints for explaining the origin. However, there is a lesson of the advanced studies of the knee region like with KASCADE, that the investigation of the far reaching astrophysical aspects by EAS observations has to be accompanied by a serious and quantitative understanding of the hadronic interactions in that energy range. That is the other side of the medal of necessary efforts! Without that, even the energy determination of EAS and scale of the spectrum may remain under debate! This debate got recently some new impact since the HiRes collaboration presented a new calibration inducing some doubt on the non-existence of Greisen–Zatsepin cut-off.

Let me conclude with the following remark. The most remarkable feature of the cosmic radiation is that the investigators have not yet found a natural end of the energy spectrum. We do not know the source of such radiation, and the features establish a mystery of great cosmological relevance.

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