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Cosmic Rays, Particle Physics and the High Energy Frontier

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1. Introduction

Cosmic rays, minute nuclear particles, are the only sample of nuclear matter that bombards us continuously from outside our heliosphere. Study of these particles is what we cosmic ray physicists do.

Extraterrestrial radiation was discovered by **Hess** some 8 decades ago in 1912. Millikan dubbed them cosmic rays. **Baade an Zwicky (**1934**),** based upon energy considerations suggested that supernovae supplies the needed energy source. It was not until late 1930s that it was shown that majority of cosmic rays are positively charged protons. It was another decade before it was shown that cosmic rays contain heavy nuclei by **Bradt and Peters** [1]. They were high energy particles whose interactions were studied after WWII and which led to the discovery of new sub-nuclear particles.

Energy of individual cosmic rays seemed to have no limit. These high energy particles were studied by observing the debris they produced in the atmosphere – air showers – following the discovery by Pierre **Auger** in 1938[2]. An air shower industry has developed since then.

Fermi, in 1949[3], theorized how these minute charged particles could reach high energies (Fermi acceleration mechanism) and lead to a monotonically decreasing power law energy spectrum. In 1966, **Greisen, Zatsepin and Kuzmin** (GZK)[4] argued that the power law might not continue for ever.

Cosmic Ray studies are intimately connected with many fields of physics and astronomy. Cosmic rays are generated throughout the universe. We only sample those that reach us. They are accelerated to high energies in relativistic shocks through stochastic processes leading to a non-thermal power law spectrum. Cosmic rays play a vital role in the energy balance of our galaxy and beyond. Cosmic rays undergo many different interactions on their journey from the sources to our earth.

They span a very wide range of energies, hence, many **ingenuous** methods for observations are needed and involve **subtle analysis** to make **grand inferences** about their origin, acceleration, propagation and interactions. Understanding of cosmic rays has progressed as new techniques developed for detectors, electronics, computing and vehicles to take us above the atmosphere. Cosmic ray research has taken us to remote locations, high altitudes, and the highest energies require large installations and large collaborations to achieve its goals.

Cosmic rays may be interstellar material, stellar material, materials in jets of energetic astrophysical sources or possibly decay products of relics of the big bang. They are accelerated by electromagnetic accelerators in energetic shocks in jets or supernova explosions or may be even in galactic clusters and collisions. The relation between cosmic rays we observe and their origin and propagation is outlined in Figure 1. I will try to show how the field of high energy cosmic ray research , since WW II, opened up new vistas in particle physics and particle astrophysics.

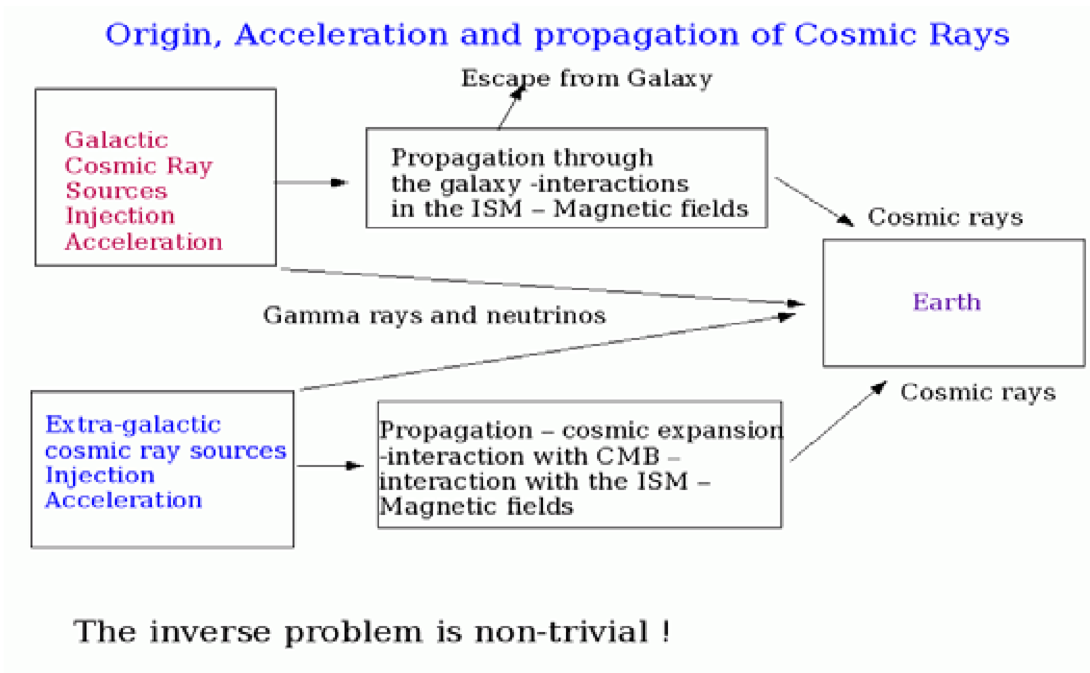

Figure 1: Illustrating the complex problem of relating observations on the earth of cosmic rays and the sources of cosmic rays.

Experiments above the atmosphere or at high altitudes detect cosmic rays traversing the instruments which measure their charge and their energy. Charge is measured through their electric interaction with matter and energy is determined either via their electric interactions and/or their nuclear interactions. A snapshot of experiments done at different altitudes is shown in Figure 2.

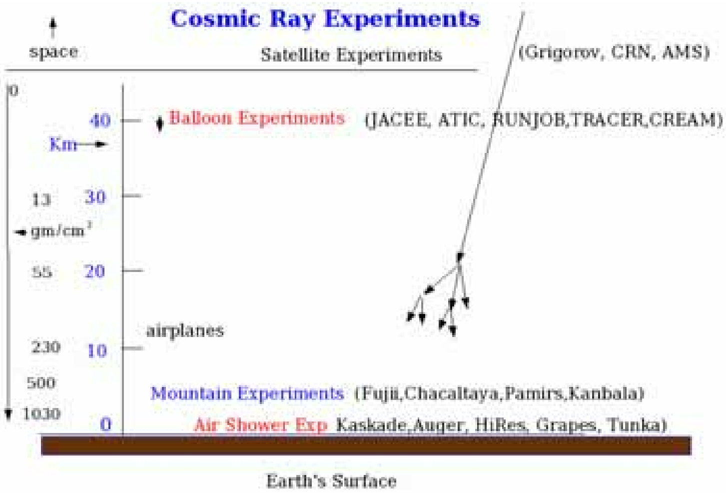

Figure 2: Recent cosmic ray experiments

Subatomic cosmic ray particles are observed through their interactions with matter. When they pass through matter they ionize and excite atoms and their presence is visualized through:

(1) Light these atoms emit – scintillation counters, fluorescence detectors.

(2) Charge they release – gas counters like Geiger counters, proportional counters.

(3) EM shock waves they produce – Cherenkov radiation.

(4) Silver grains they leave behind in photo emulsion.

(5) Droplets they form in cloud chambers.

(6) Transition radiation at interfaces.

(7) Synchrotron radiation in magnetic fields.

Their passage can be located with high precision and their tracks can be traced. Collisions of cosmic rays with nuclei produce a multitude of new subatomic particles which can be studied.

The energy of cosmic rays can be estimated from the energy deposited by the particle in a block of absorber – which could be dense material like iron or lead or which could be tenuous material like the atmosphere. Experiments which use the atmosphere as the detector are called air shower experiments. A schematic of a ground based shower detector is shown in Figure 3 and a schematic of a balloon experiment is shown in Figure 4.

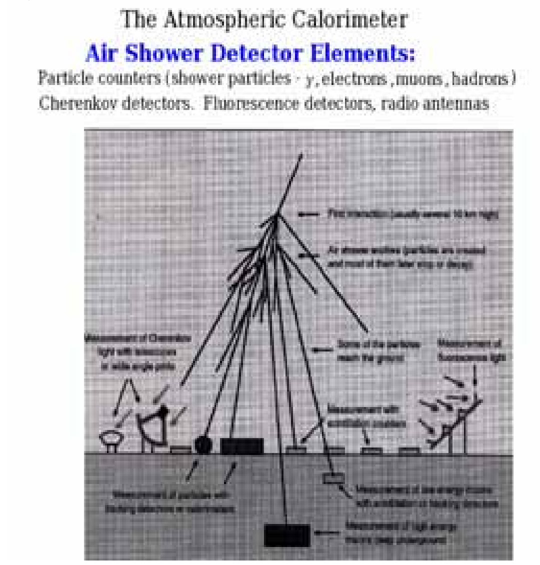

Figure 3

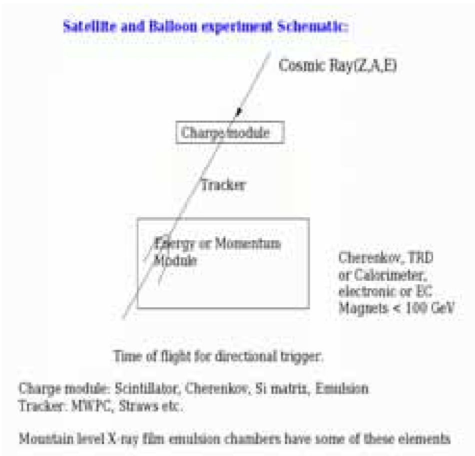

Figure 4

Many subatomic particles were first discovered in cosmic rays: **positron, muon, pion, anti-proton, kaon and other strange particles**. In the last two decades cosmic rays have advanced the study of the elusive neutrino. Neutrino oscillations were observed with neutrinos produced by atmospheric cosmic rays and neutrinos originating in our sun.

The talk will outline the current outstanding challenges of this very active and alive field. **I will discuss our understanding of cosmic rays over the whole energy range and their impact on understanding hadronic interactions at high energies.** May be solutions to some of the challenges will be presented at this Cosmic Ray conference.

2. Personal Introduction

I came to Chicago when cosmic ray physics was actively being pursued by the groups of **Marcel Schein** and **John Simpson**. There were cloud chamber experiments at mountain altitudes and emulsion chamber stacks were flown at high altitudes by ballooning. **Fermi** developed his theory for the origin and acceleration of cosmic rays by stochastic processes in collisions of cosmic rays with moving magnetic clouds. I was introduced to cosmic ray research through working for **Jere Lord** in the Schein group studying 10s of GeV cosmic ray interactions with emulsions. I have pursued the study of cosmic rays and their interactions since.

2.1The Particle Zoo

In the years 1946 to 1954, cosmic rays discovered a zoo of elementary particle states from starting with the pion in nuclear emulsions flown at high altitudes, the V particles (Lambda, Sigma baryons and K mesons) in nuclear interactions of cosmic rays using a variety of new techniques. They also discovered multi-particle production at 10s to 100s of GeV energy cosmic rays. With the same techniques heavy nuclei and electrons in cosmic rays were observed. Also discovered were secondary cosmic ray nuclei like Li, Be B which were very scarce in universal abundances, produced by collisions of primary cosmic rays with ISM[5]. Some examples are shown in Figure 5 of the detection of new subatomic particles in cosmic ray experiments: The discovery of the pion and of the V particles in the late 1940s in emulsions and cloud chambers.

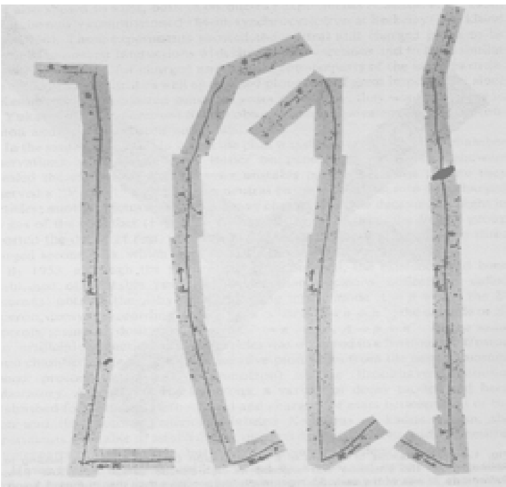

Figure 5: (a) Pion decays (b) Production of a V particle.

In 1951, at the International Conference on Fundamental Particles in Chicago at least 21 subatomic particles were known. Fermi in his introductory speech said:
' Philosophically, at least some of these 21 particles must be far from elementary! The requirement for a particle to be elementary is that it be structureless.' It took two decades since this speech before the particle zoo was classified and standard model of elementary particles was established explaining the particle levels in terms of interactions of quarks and gluons with QCD.

The first extremely high energy event discovered in cosmic rays was the **Schein star.** It was a 300 GeV interaction observed in emulsion which was a remarkable observation of multi-particle production of hundreds of secondaries. This event is shown in Figure 6 [6].

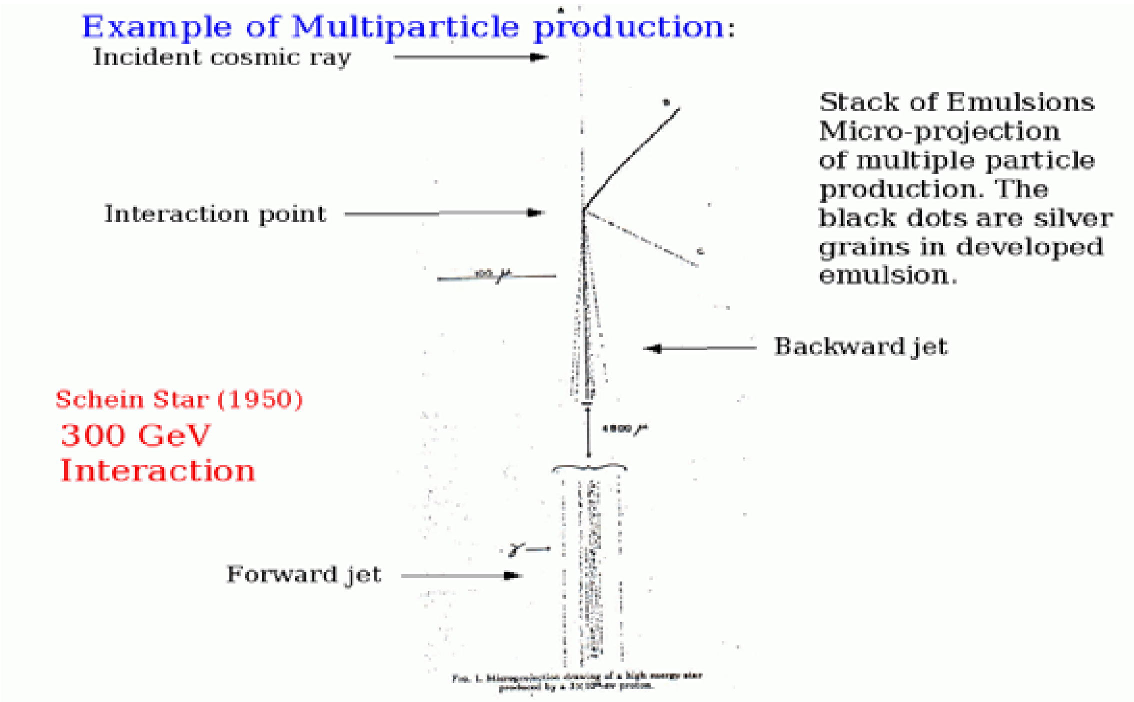

Figure 6: The Schein star.

3. The Cosmic Ray Beam

Cosmic ray intensity measured as a function of energy is called the cosmic ray energy spectrum. It is: Number of particles crossing a unit area, per unit solid angle, per unit energy interval per second or particles per m^2, *sr, sec, GeV* .

In every day life we measure energy in calories or joules. Subatomic particle energies are measured in electron-volts (eV), which is a tiny number in joules: 1.6×10^{-19} joules Cosmic rays have energies which vary from a few GeV (1 GeV = 10^9 *eV*), to very large energies : 10^{20} eV which corresponds to an energy of a fast baseball concentrated in a single subatomic particle ! The LHC will reach only 10^{17} eV.

Cosmic ray energy spectrum is shown in Figure 7 extending from about 100 GeV to the highest energy given above. It is relatively smooth decreasing by about a factor of 100 every decade in energy. There are several features if one looks closely. These are the knee, the 2nd knee, the ankle and possibly a cutoff called GZK cutoff. These features can be made more visible by plotting a graph of the energy spectrum multiplied by the cube of the energy. This is shown in Figure 8:

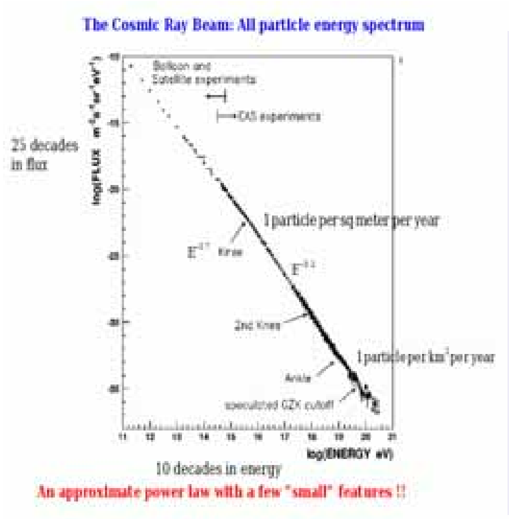

Figure 7

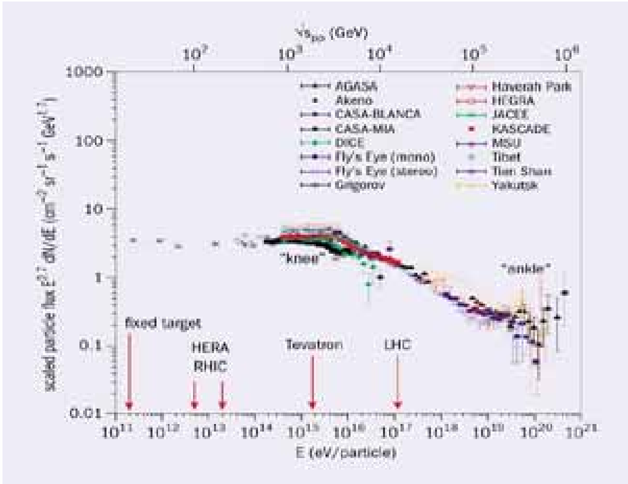

Figure 8

The primary focus of cosmic ray studies is to understand their origin, acceleration and propagation over this enormous energy range. As cosmic rays provide a source of extremely energetic particles their study also explores with cosmic rays their interactions at high energies.

Current paradigm for the bulk of cosmic rays is that they are interstellar atomic nuclei or stellar wind particles accelerated by shock fronts generated by supernova explosions in our galaxy[7]. The galactic supernova rate combined with the average residence time of cosmic rays in the galaxy account for the energy content of cosmic rays.

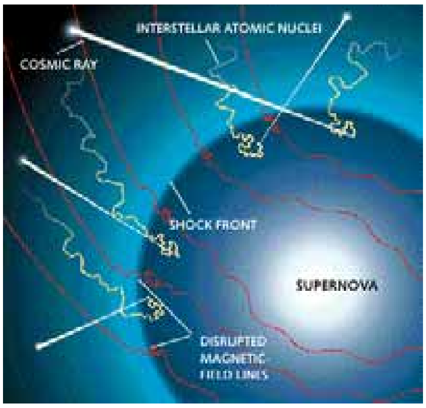

Figure 9

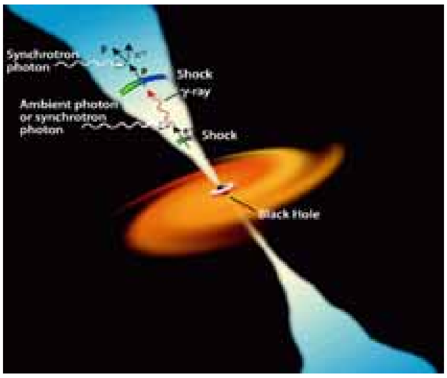

Figure 10

It is also theorized that cosmic rays are accelerated in energetic jets emanating from black holes formed in gamma ray bursts (GRBs) and in active galactic nuclei(AGNs)[8]. These objects are also sources of high energy gamma rays which have been observed by VHE gamma ray telescopes. Figures 9 and 10 show ' cartoon ' sketches of these. For the case of acceleration in supernova explosions, the shock wave acceleration lasts until the shock dissipates in a time T, Maximum energy that can be achieved depends on this life time and on the charge Z of the cosmic ray nucleus. $E_{\max} \propto ZT$. This energy is called the ' rigidity' cutoff energy beyond which energy spectra from supernovae should steepen or cutoff. This is considered to be the origin of the knee in the cosmic ray spectrum shown in Figure 8.

The current paradigm for the subsequent flattening of the cosmic ray spectrum at around $10^{18}\ eV$ attributes it to contributions from extra-galactic sources distributed over all red shifts due to energy loss from electron-positron pair production. Finally one expects a further cutoff of the extra-galactic cosmic ray spectrum due to nuclear interactions of cosmic rays with the all pervading cosmic microwave background(CMBR) radiation, the GZK cutoff, providing for energy loss at the highest energies. We will discuss all these effects [9] in section 6.

3.1 The knee region and Rigidity cutoff models:

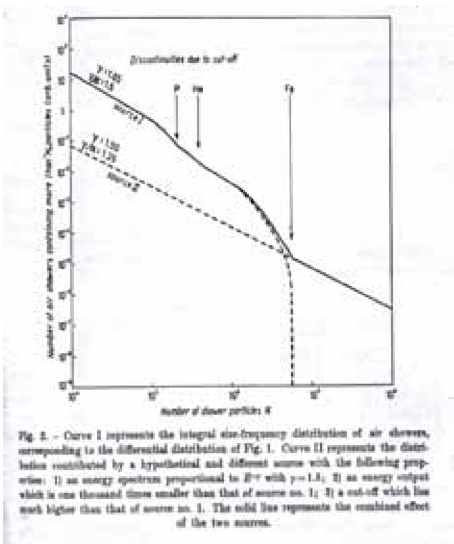

Figure 11

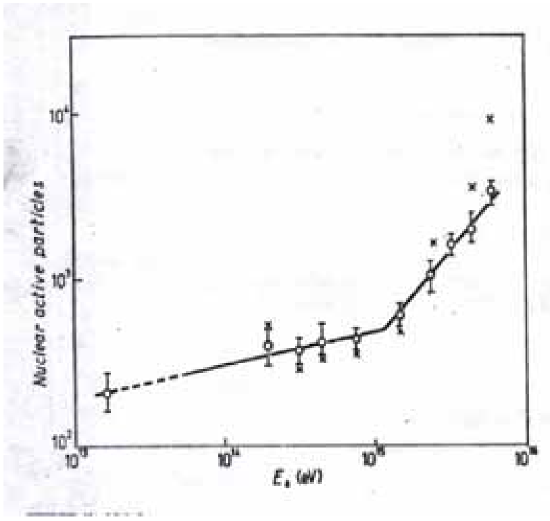

Figure 12

A rigidity cutoff model for galactic cosmic rays was developed by Peters in 1958[10] to provide a simple model to explain the nuclear active particle content of air showers. He invited me to work on his equilibrium model of shower propagation which made it possible to analytically calculate shower properties of interest before the age of computers. We showed we could explain experimental observations with this simple model in which cosmic rays became enriched in heavy nuclei as a consequence of rigidity cutoff. The model left out pion cascades. I was familiar with pion physics having worked with Fermi and Panofsky on pion interactions and production. I was not satisfied with this simple model. So with D. Sankarnarayan[11], I developed a model including pion cascades which also explained the experiments without needing a rigidity cutoff ! This was my introduction to air shower physics and its complexities. Peter's rigidity cutoff model was developed to explain an experiment which seemed to show a dramatic increase in the number of nuclear active particles (hadrons) as a function of energy just at the location of the knee. Work of Peter's and its explanation of the air shower results are shown in Figures 11 and 12.

The determination of the composition of cosmic rays from indirect experiments is a difficult one. Different experiments led to different conclusions, which I illustrate with several quotes from experimental papers on composition near the knee:

“ the composition of cosmic rays is varying with energy..... from being dominated by protons and lighter nuclei below $10^4\ GeV$ to becoming dominated by heavy nuclei between 10^5 and $10^6 GeV$ ” , Goodman et al., 1982 (Delayed Hadrons in air showers[12])

“ No evidence for a large change in the mean mass of cosmic rays across the knee.” Swordy and Kieda (1999) (DICE Cherenkov experiment [13])

“ ..there is no doubt about the general trend : the mass composition gets heavier at energies above the knee observed in the all particle spectrum and the knee originates from the vanishing of the light component ” Haungs, Rebel and Roth(2003) (KASKADE experiment.[14])

3.2 Composition by direct observations

Improved ballooning techniques developed after WWII made it possible to fly instruments at high altitudes to measure the cosmic ray composition directly. Emulsion stacks and electronic telescopes were lifted up to high altitudes. Below 100 GeV much work was done by Peters, Weber and others with emulsion stacks and later by Ryan et al [15]who flew an iron calorimeter. Some of the early efforts for ballooning were at TIFR in Mumbai and I show in Figure 13 the group working on ballooning in India and a more modern version of an high altitude balloon.

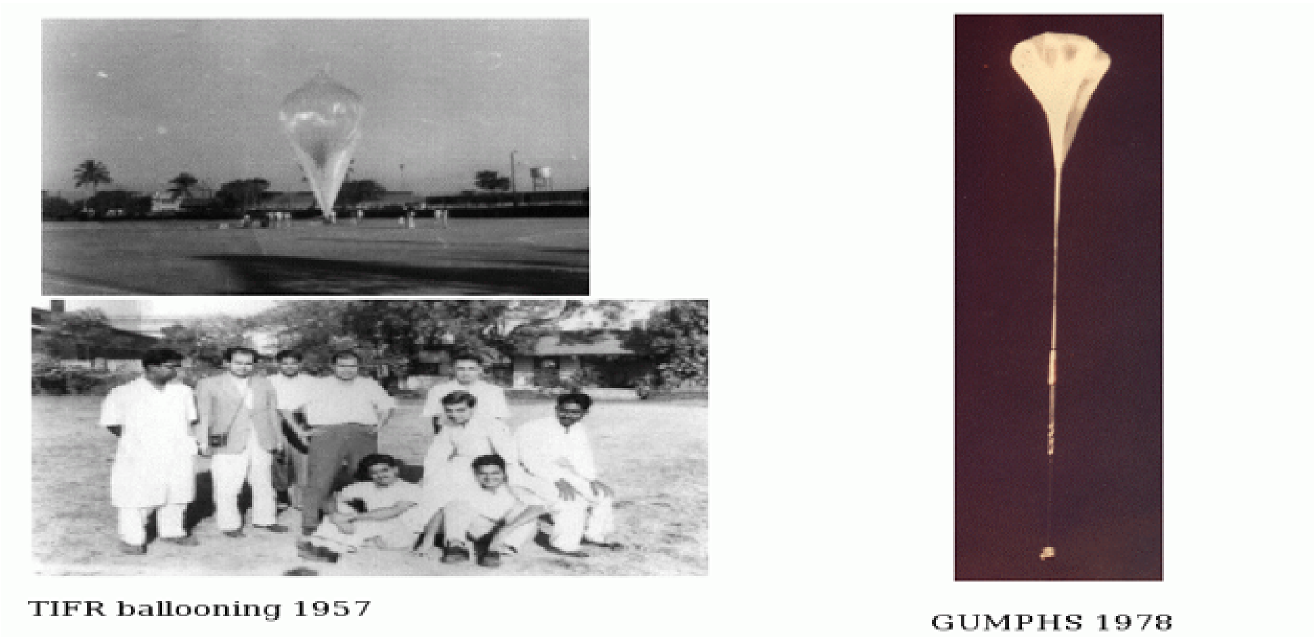

Figure 13

Three current experiments for direct measurements , TRACER, ATIC and CREAM are shown in Figure 14, [16,17 and 18].

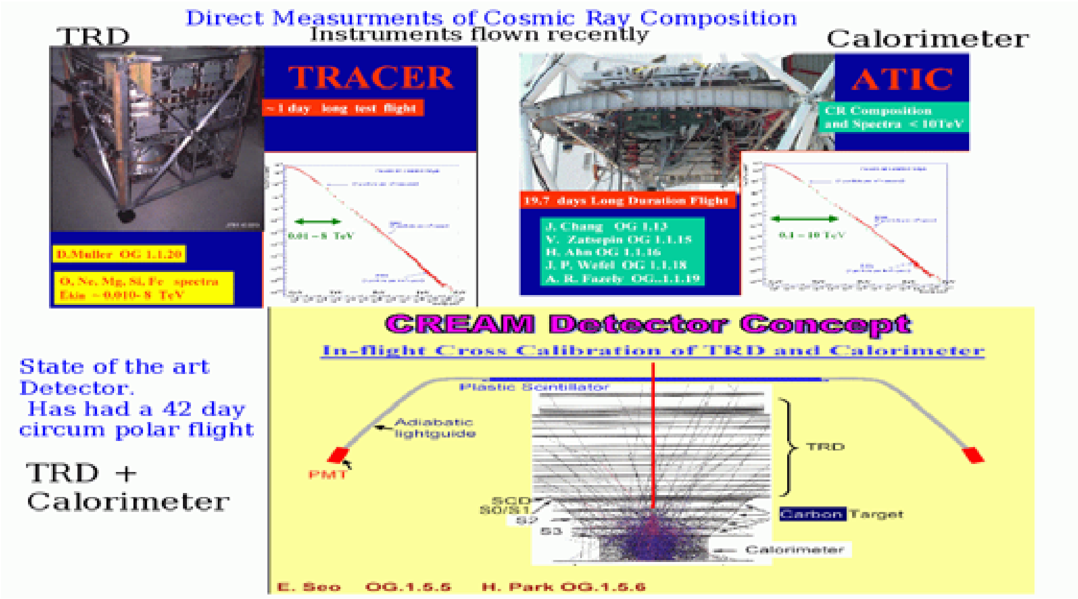

Figure 14

The quality of these results for the energy spectra of individual elements is shown in Figure 15:

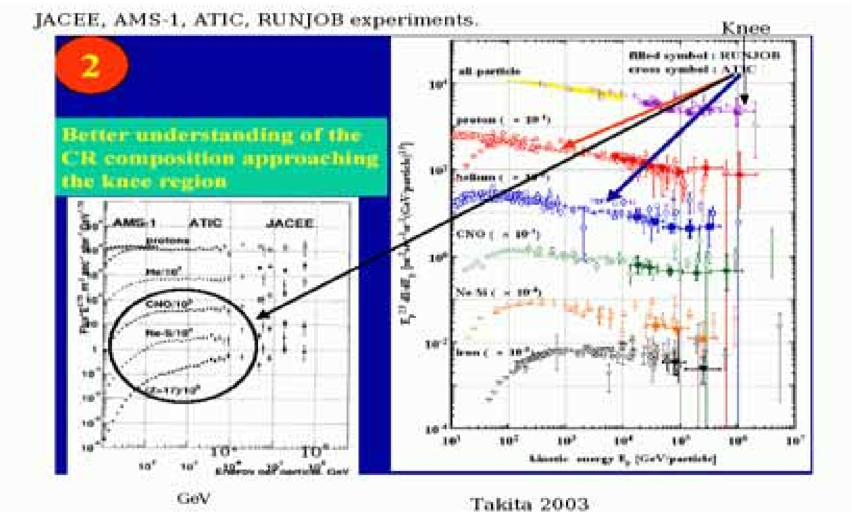

Figure 15

From the results of these direct experiments the average logA can be determined as a function of energy. These results are shown in Figure 16. One sees that JACEE[19] and RUNJOB[20] results are different at the highest energies, however the statistics are not sufficient to resolve the question whether the average logA is increasing just below the knee energy of $10^{15}\,eV$ or not.

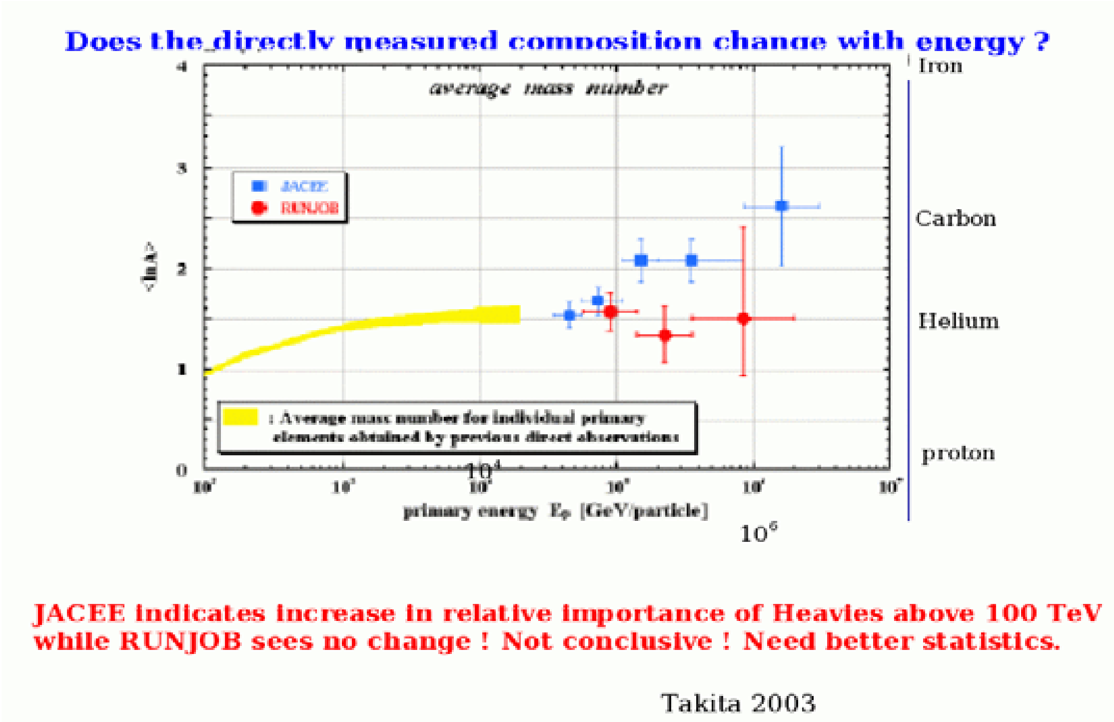

Figure 16

3.3 Exploring Higher Energies:

This is done with indirect techniques. There are three techniques: (1) Mountain level emulsion chambers from 10 TeV to 1000 TeV; (2) Underground, water or ice detectors for detecting neutrinos for energies 10 TeV or above and (3) Air shower detectors from 100 TeV to 100 EeV which can consists of (a)Ground Array only – KASKADE , AGASA[21], AUGER[22], (b) Air Cherenkov arrays – TUNKA[23], BLANCA[24], CACTI[25], DICE[13]; (c) Air Fluorescence detectors with or without a ground array – HIRes[26], AUGER; (d) RADIO arrays or detectors – RICE, LOPES and ANITA. In all of these energy is sampled by calorimetry, mass of incident particle is not measured directly and all rely on simulations in interpreting the experimental measurements. It is the age of calorimeters.

The growth of these experiments in high energy cosmic ray research beyond the knee of the spectrum is shown in Figure 17. Also shown in the figure are the mountain level emulsion chamber experiments at Chacaltaya [27], Mt. Fuji [28], Kanbala [29] and Pamirs [30] which studied particle interaction properties by observing individual high energy events and also by observing spectral index of the energy spectra of atmospheric jets in their detectors. The latter is sensitive to attenuation of primary cosmic rays at 100 to 1000 TeV in the atmosphere and hence to the inelastic proton-air cross section discussed a little later. Also indicated on the plot are some of the direct experiments done at high altitudes by ballooning and the proton-satellite experiments of Grigorov and collaborators.

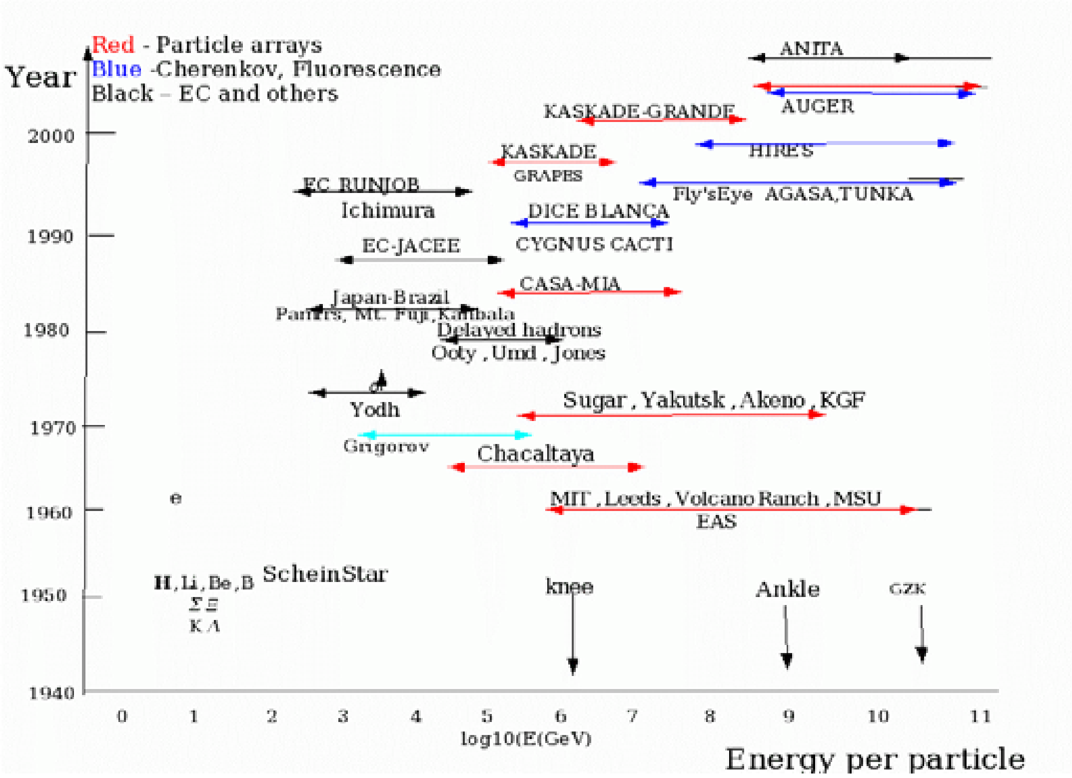

Figure 17

4. Particle Physics using Cosmic Rays: 10 TeV to 10,000 TeV

The highest energies explored by accelerators until late 1960, before the advent of colliders, corresponded to cosmic ray energies of few 100 GeV. So cosmic ray beam offered the only means of investigating higher energy hadron interactions. Cosmic ray experiments done at high altitudes with a variety of techniques led to first indications of new properties of high energy particle interactions(1970 -1990). Cosmic ray experiments were first to establish the following properties of hadronic interactions which were later confirmed by collider experiments:

(1) Increase of hadronic cross sections [31];

(2) Increase of nucleon-anti-nucleon production in high energy collisions[32];

(3) Increase of average transverse momentum with particle multiplicity and

(4) rise of psuedo-rapidity plateau at high energies[19].

4.1. Rising cross sections

In the 1960 the high energy paradigm was that interactions obeyed scaling and cross sections had reached their asymptotic high energy limit and should be constant. This was first shown not to be correct by analysis of cosmic ray experiments to estimate the penetration of cosmic ray protons through the atmosphere without interaction (surviving). This fraction depends on the probability of proton-air inelastic collisions. By comparing unaccompanied mountain level high energy hadron flux with the primary flux at the top of the atmosphere a lower bound to the proton-air inelastic cross section is obtained[31]. Figure 17 shows the principle of the method and the rising lower bound that was deduced. Soon after this prediction, CERN ISR experiments actually measured rising proton-proton cross sections at high energies.

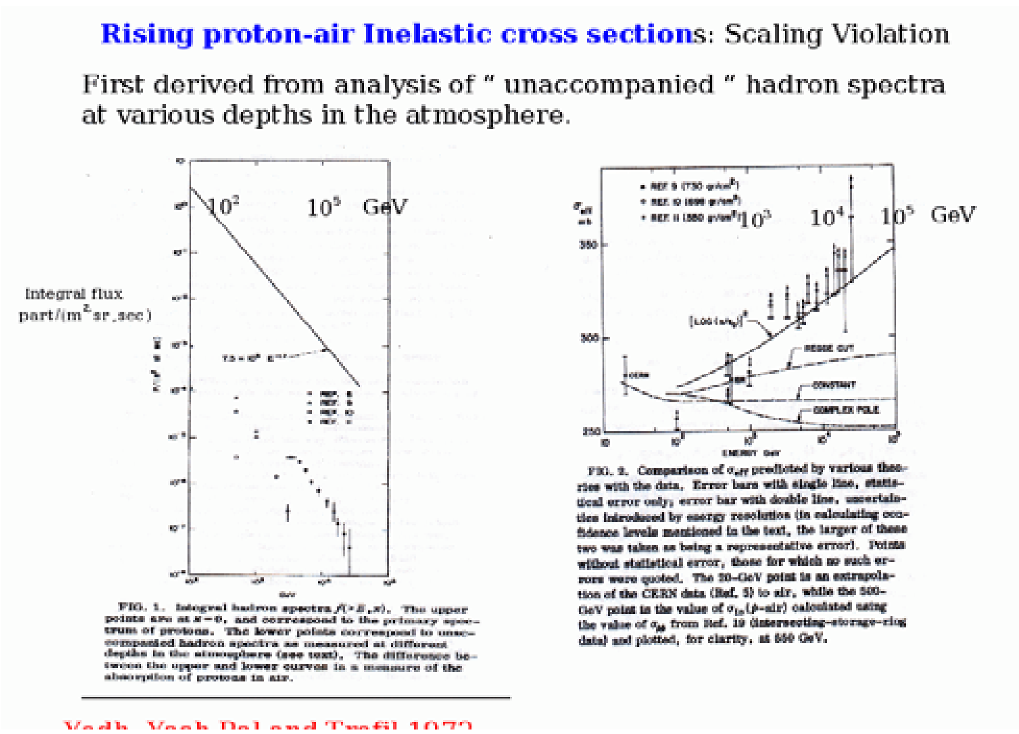

Figure 17

What is derived by analysis of cosmic ray experiments is proton-air inelastic cross section. At highest energies, cosmic rays still offer the only experimental access to deducing proton-air cross sections and analysis of AGASA and Fly's Eye data confirmed

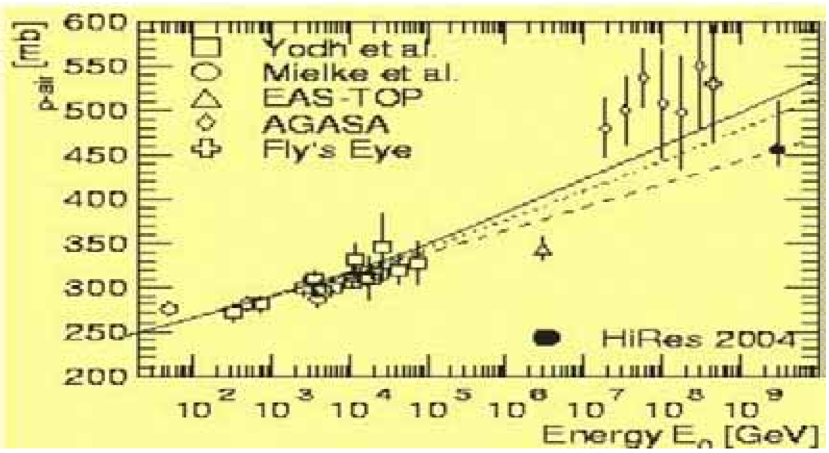

Figure 18

the continued rise of the cross section as shown in Figure 18[32]. The anti-proton proton colliders, S-pbar-p-S and the Tevatron confirmed the rise in proton-air cross section seen in cosmic rays in direct measurements of total cross sections in p-bar p collisions.

4.2 Increase of Nucleon anti-nucleon production

In a series of experiments done at Ootacamand, India, Tonwar and Sreekantan [33] studied the distribution of delayed hadrons of relatively high energy in air showers and showed that the observations required substantial production of anti-nucleon, nucleon pairs in high energy collisions at about few 100 to 1000 TeV energies. This conclusion was later confirmed at ISR and higher energy machines.

4.3. Study of gamma families and properties of high energy interactions

Pioneering emulsion chamber experiments were: Japan-Brazil at Mt. Chacaltaya, Yuda's group at Mount Fuji, Slavatinsky's Pamir collaboration, China-Japan collaboration at Mt. Kanbala, Japan-American collaboration(JACEE) and by Niu and collaborators using balloons and emulsion chambers. Conference at Bartol in 1978 brought many of these collaborators together to examine these results. Figure 19 shows the meeting group photo:

Figure 19

Figure 20

Figure 20 shows four pioneers who did high energy cosmic ray experiments : from right to left: Sreekantan, Nikolskii, Fujimoto and Slavatinsky.

Particle physics results obtained from the study of jets from interactions produced locally in a target in the 10 to 100 TeV range (Japan-Brazil C-jets and JACEE balloon events) all indicated violations of the then current paradigm of scaling in observation of increase in average transverse momentum with jet multiplicity, rise of the central region of the rapidity plateau not expected from scaling and increase in jet multiplicity faster than logarithmic with energy. These observations were harbingers of QCD and of large pt processes[34].

5. Still Higher Energies: Shower Experiments

Although there are cosmic rays at higher energies their flux decreases rapidly, and different techniques are needed to observe high energy cosmic rays and their interactions.

The atmosphere is used as an **amplifier** to increase the area of influence of a single high energy particle. It is also used as a **calorimeter** to measure the particle energy.

Shower experiments sample different features of the development of particle cascade produced by cosmic rays in the atmosphere. For each shower one determines its direction, its longitudinal development and lateral spread of different shower particles and infer from these measurements the energy and nature of the cosmic ray initiating the shower. The shower particle swarm moves close to the **speed of light** and arrives at the observation level as a curved **pancake of relativistic particles.** Timing of the pancake is used to find the direction of incident primary. The maximum of the shower cascade can be determined by the direct observation of the longitudinal development of the cascade using either fluorescent light or Cherenkov radiation. The timing of individual shower particles and their directions can also be shown to depend on position of shower maximum.

The **composition inference** is indirect and involves detailed **simulations** which require a knowledge of physics of high energy particle interactions and the characteristics of the shower detectors. The mass dependence can be inferred from the the position of the **depth of shower maximum** in the atmosphere, or from the muon content of the shower. Muons, once they are produced through decay of pions or kaons etc do not interact, and measuring their total number can provide an estimator of the mass A, because heavy nuclei interact **higher** up in the atmosphere where **decay** of unstable particles can be more important relative to their interactions. It is a difficult inverse problem. The main types of detectors to sample cosmic ray showers are:

Fluorescence detectors: Longitudinal development of the shower can be determined by observing PH and timing of Nitrogen fluorescence light produced by shower particles as the cascade develops through the atmosphere, reconstructing direction and energy and position of shower maximum of the event. Simulations used to determine the mass of primary particle.

Ground arrays determine pulse height and time of arrival of particles on the ground, determine sizes (electron, muon and hadron) and core position and use this information to determine direction and estimate the energy and mass of the primary through simulations.

Combination of Fluorescence and ground array can inter calibrate energy estimates and improve the mass determination. Events for which both fluorescence and shower particle distributions at observation level can be determined are called **hybrid** events and provide the best information about the energy and type of the primary cosmic rays.

In figure 21 I show a collection of photographs of some of the pioneers of air shower experiments:

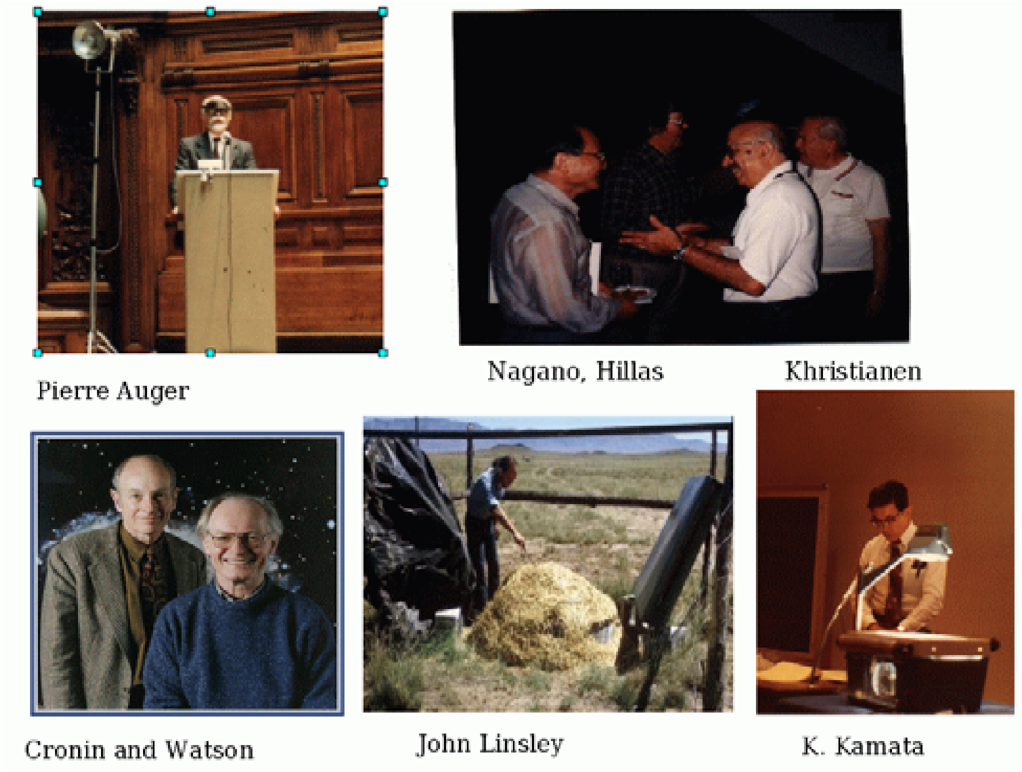

Figure 21

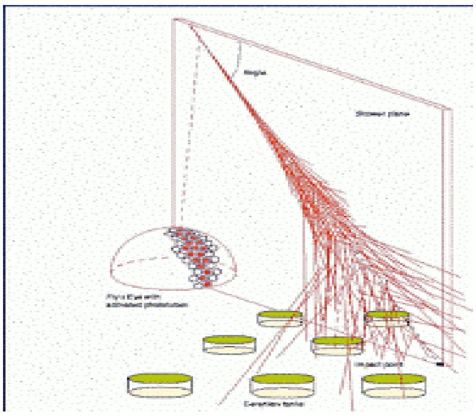

Figure 22

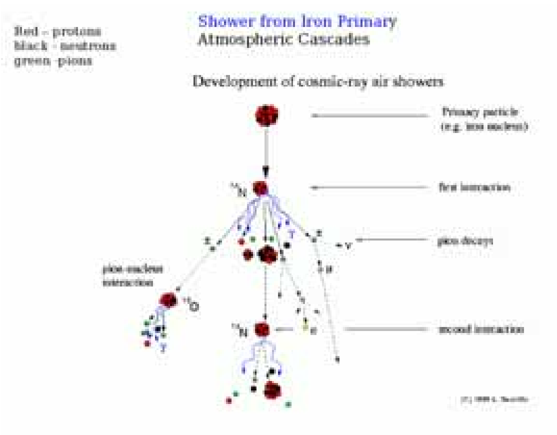

Figure 23

A schematic of an air shower experiment which uses both a ground based array and a fluorescence detector is shown in Figure 22, which represents experiments such as Auger and Hi-Res Mia . Figure 23 shows a schematic of a nuclear-electromagnetic shower cascade development in the atmosphere.

The longitudinal development of a shower is represented by the variation of the number of shower particles as a function of slant depth of the shower. This curve shows the initial rise of the number of particles in a shower and then gradual exponential decay after reaching a shower maximum. This curve fluctuates from event to event depending on the stochastic nature of particle interactions. Idealized cascade curves and their fluctuations, for primaries of the same energy, are shown in Figure 24 for two different types of shower particles: soft component (electrons and positrons) called N_e and penetrating component (muons) called N_μ.

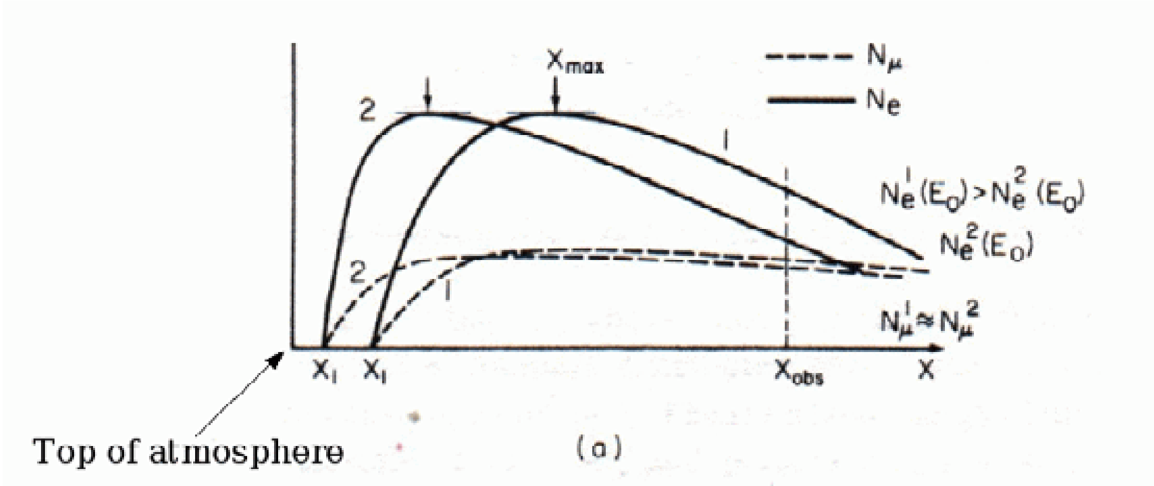

Figure 24

In spite of shower fluctuations from event to event, it is possible to relate the average values of shower parameters to the energy and atomic mass of the primary. The total energy of the shower can be estimated by different techniques, which are:

(a) total fluorescence light from the cascade(Fly's Eye, Hi-Res),
(b) the Cherenkov light emitted by relativistic charged particles in the showers (TUNKA, BLANCA, DICE, CACTI),
(c) the electron and muon content and their distributions in the shower (KASKADE, AUGER) and
(d) the coherent radio emission from charged particle cascade (LOPES, RICE, ANITA).

Calculations of these quantities require detailed simulations in which particle physics is an essential input. The inverse problem, to derive event by event information about the primary, its energy and its mass, is made quite difficult by the fluctuations pointed out above. The current ' standard ' models are versions of QGS-jet and SYBILL simulation programs which describe particle interactions and their energy dependences which are incorporated in various shower codes (KORSIKA, AIRES etc). Particle interaction experiments do not extend into the high energy cosmic ray region and information on particle -nucleus collisions has to be inferred; therefore these models agree in the region where direct data are available but diverge at higher energies.

If the energy of an individual shower event is measured by an air shower experiment, then the mass of the primary, A, may be estimated from

(a) the position of the depth of maximum[35],
(b) correlation between the muon and electron content of the shower,
(c) correlation between hadronic and muon or electronic content of the shower or
(d) by a combination of these measurements[36].

The dependence on atomic mass is generally proportional to log A, a quantity which varies between 0 for proton initiated showers and 4.2 for iron initiated shower. In a superposition model the dependence of position of shower max is related to energy and atomic mass as

$$: X^{A}_{MAX} = X_0 + X_1(\log_{10}(E) - \log_{10}(A))$$

a linear dependence of X_{max} on log(E) with a different magnitude for X_{max} for different atomic species of cosmic rays. Figure 25 is a compilation of most of the measurements of depth of shower maximum as a function of energy as compared with expectations from simulations for different primaries – gamma primaries, proton primaries and iron primaries.

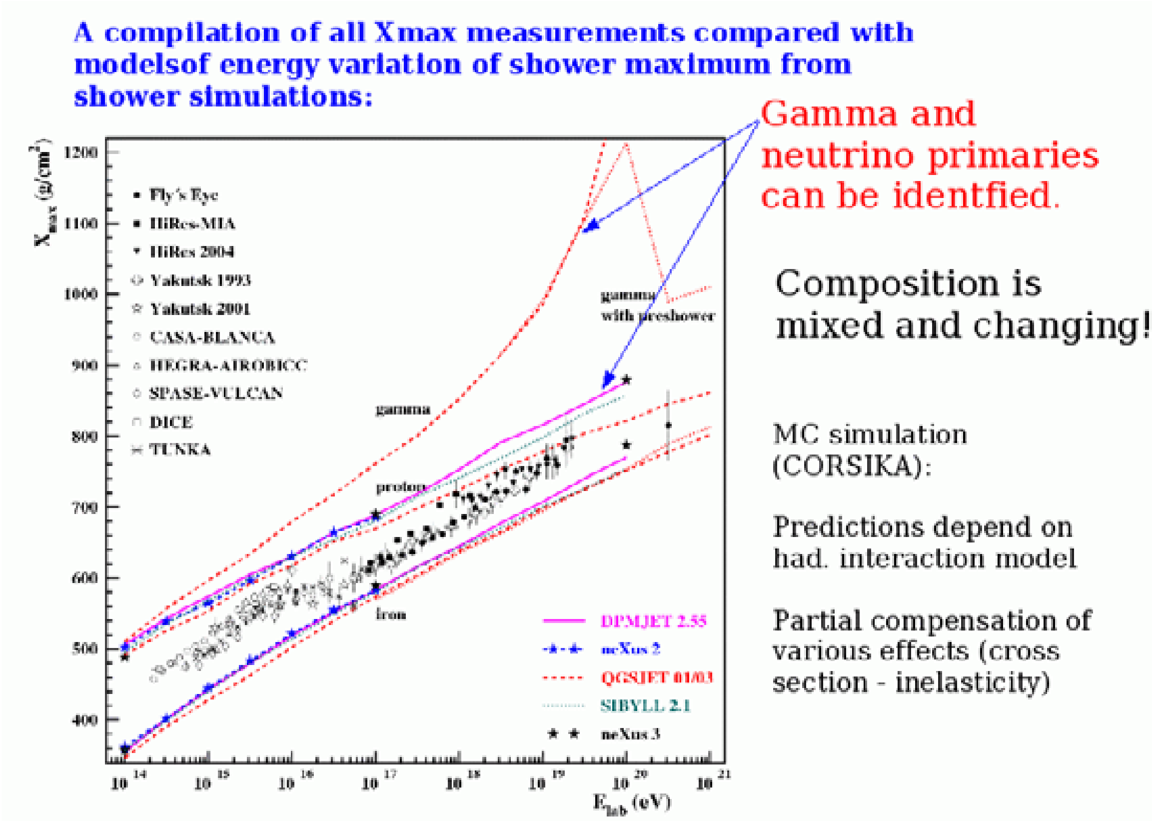

Figure 25

In my opinion, this figure means that composition of cosmic rays is mixed and is changing with energy. It is possible that the mix of cosmic ray nuclei at highest energies becomes lighter and around 100 PeV it is enriched in iron. The enrichment in the knee region is probably consistent with rigidity cutoff of cosmic rays produced and accelerated in supernova explosions. Again note that the conclusion is particle physics interaction model dependent.

There are many other air shower experiments currently operating which measure the spectra of cosmic rays and their masses by ground based air shower experiments without the knowledge of the longitudinal development, shower by shower. These experiments are shown in Figures 26 through 29. The largest array at present is AUGER shown in Figure 26. HiRes is schematically shown in Figure 27.

Figure 26

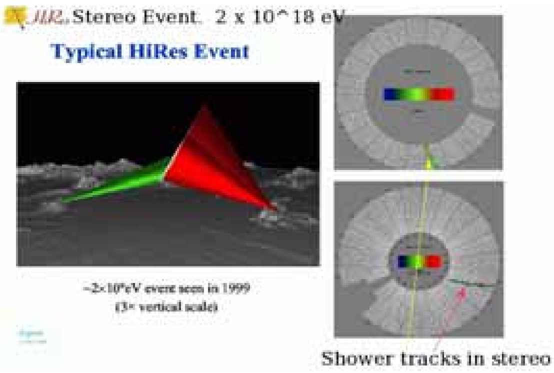

Figure 27

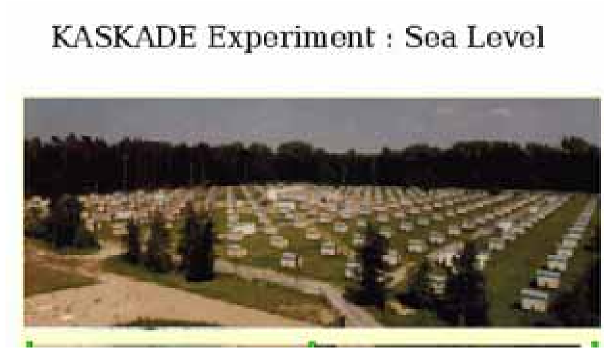

Figure 28

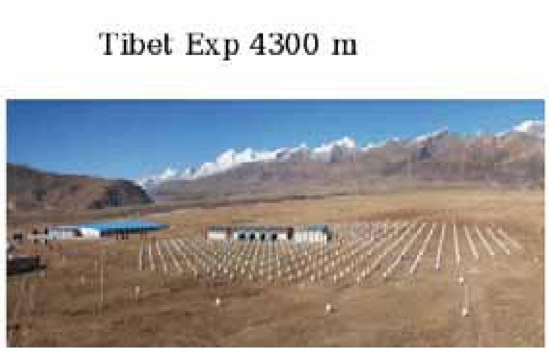

Figure 29

The Auger experiment is just turning on and we hope to see results at ultra high energies from them. HiRes has presented results from their monocular analysis and I will mention their results later. The KASKADE[14] and TIBET[37] experiments cover the energy range of the knee of the cosmic ray spectrum around a PeV and they have obtained similar results for the all particle spectra but differing results for the elemental composition. I present the current elemental spectra measured by KASKADE and the proton spectrum measured by Tibet. The KASKADE experiment sees a proton rigidity at about 3 PeV, while Tibet experiment with very different techniques see a proton spectrum which steepens around 0.5 PeV. In the knee region we have **not** reached a consensus on what is the composition mix of cosmic rays nor as to how exactly the energy spectra of different species steepen through the knee region. This situation is shown in Figures 30 and 31. The current status of estimation of mean logarithmic mass of cosmic rays as a function of energy is given in Figure 32.

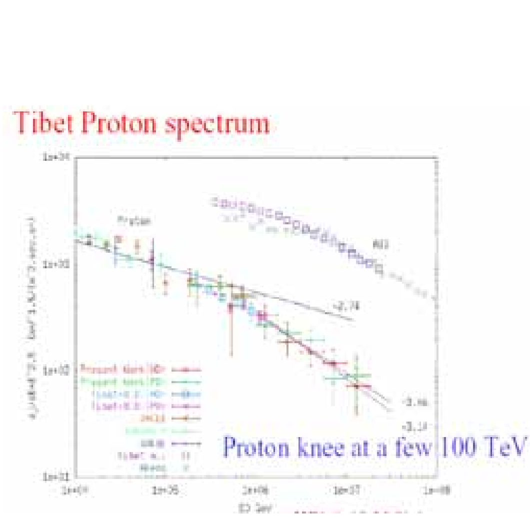

Figure 30

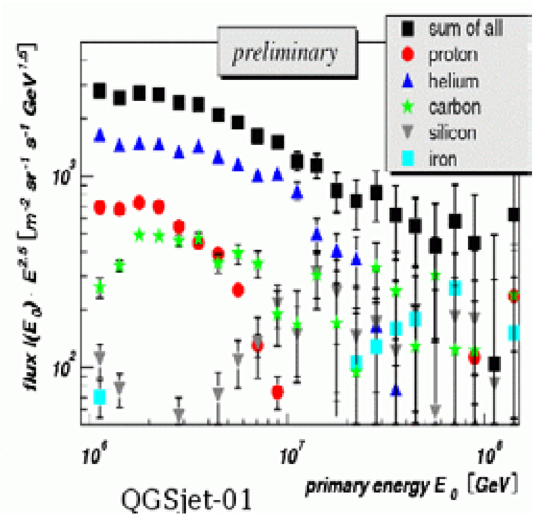

Figure 31

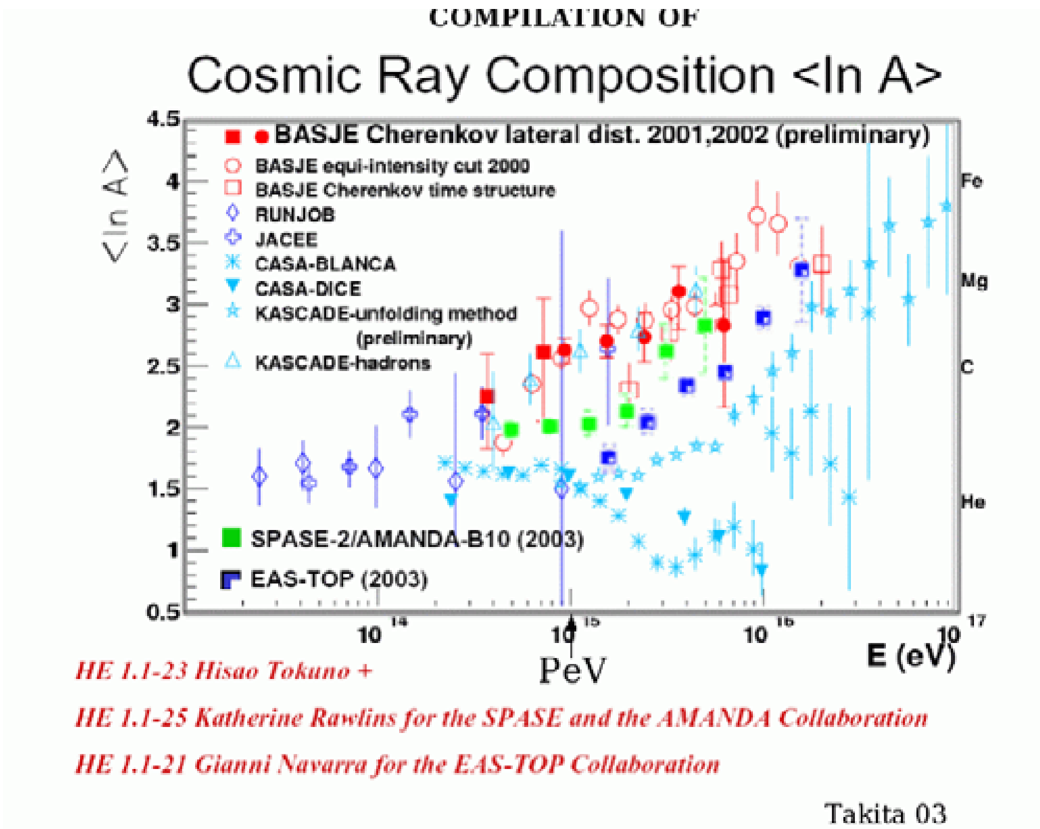

Figure 32

Conclusion: We need better experiments in the knee region to unravel the question of whether the composition becomes heavier or not due to Peter's cycles – rigidity cutoff in cosmic rays accelerated by supernova explosions.

6. Highest Energy Cosmic Rays

I conclude with a discussion of the highest energy cosmic rays, in the energy region from 100 PeV (10^{17}eV) to 100 EeV (10^{20}eV). This region includes what is called the second knee, the ankle and the GZK cutoff and beyond. Open questions are:(a) where does the spectrum of galactic cosmic rays end ? (b) if cosmic rays of energies above an EeV are extra-galactic what causes the ankle (slight flattening of the energy spectrum) in the 1 EeV to 10 EeV region? (c) is there the expected GZK cutoff due to interactions with CMBR ? and (d) what is the origin of particles with energies above 100 EeV?. I discuss the recent results from HiRes experiment on the shape of the ankle and on hints for the GZK cutoff in terms of a model proposed by Berezinsky[9].

Berezinsky proposed a " Uniform Source Model (USM) for extra-galactic cosmic rays. His assumptions are: that there is a distribution out to large redshifts of cosmic ray sources all of which have a common spectral slope $-\gamma$ and are 'standard' candles and are source of high energy protons. He allows for evolution of the form $(1+z)^m$. Protons loose energy in their propagation to the earth due to interactions with the CMBR.

Two particle interaction processes are included: electron-positron pair production and pion production. The cosmic ray flux at earth is then the sum of the contributions from all of these sources. The nearest sources are responsible for the highest energy cosmic rays through the GZK cutoff. The ankle and the pile up at 50 EeV is due to modification of cosmic ray spectra from distant sources due to energy losses considered above.

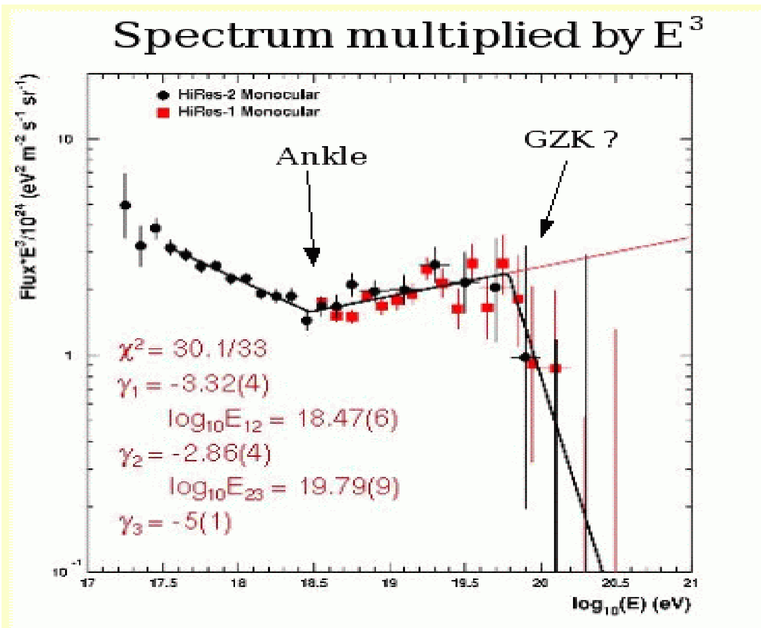

Figure 33

The monocular spectrum by HIRES experiment is shown in Figure 33 [26].

The figure shows clearly what is meant by the ankle, after the second knee and then the indication of the GZK cutoff. AGASA points are not included in this figure. The AGASA data shows no GZK cutoff. The lines are fits to the data and help guide your eye as to what is the second knee, what is the ankle and what is the steepening beyond 50 EeV.

The expected results for the Berezinsky model are shown in Figure 34. Blue lines represent nearby extragalactic sources and red lines correspond to distant sources at large redshifts. A fit to the model parameters for spectral slope and evolution index is made in Figure 35 using the data in Figure 33.

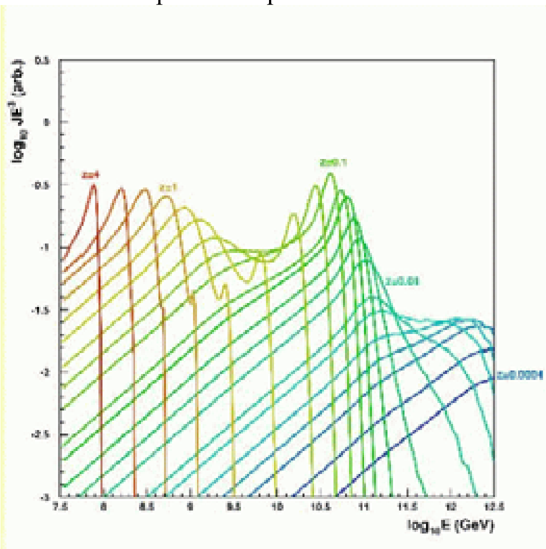

Figure 34

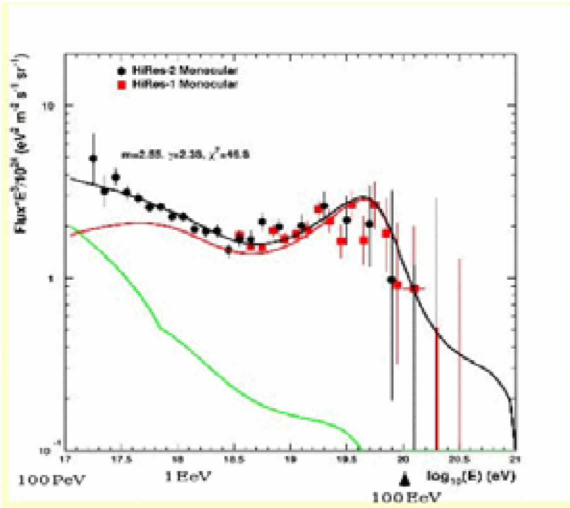

Figure 35

Berezinsky model can be made to fit with highest energy data. It requires a spectral index for the ' standard ' extra-galactic sources of -2.38 and an evolution index of 2.55 and the galactic spectrum has to fall steeply beyond 100 PeV. What determines its fall off ? What are these standard candles ? How are cosmic rays accelerated to such high energies – these are still open questions.

7. Concluding remarks

Cosmic rays physics is alive and healthy. It has contributed to development of particle physics: discovery of the particles such as the pion, muon, positron, and strange particles, the deduction of increasing hadronic cross sections with energy all the way up to the highest energies, indications of violations of scaling in particle interactions and hints of high transverse momentum events in mountain level emulsion chamber events. May be dark matter signatures will be found in cosmic ray experiments or in top down scenarios we may explore the physics at ' unreachable energies' in the laboratory.

We still do not have definitive models for the origin, acceleration and propagation of cosmic rays[8]. The energy region from the knee to the second knee (1 to 100 PeV) needs better and more definitive experiments to measure the mass composition of galactic cosmic rays. Different experiments do not agree as to the location of the rigidity cutoff and search for local sources remains enigmatic. Still open is the question as to up to what energies do galactic cosmic rays extend ? Are the highest energy galactic cosmic rays heavy nuclei ? The region above an EeV is where the action frontier is at present. Are there cosmic rays beyond the GZK cutoff , if so what are they? AUGER and HIRES should answer these questions.

I want to thank the organizers of this ICRC for their invitation to give the HESS lecture. It gave me an opportunity to bring together the many years of cosmic ray and particle physics research I have pursued. In preparing this lecture I had to make difficult choices and leave out discussing many of the experiments included in summary figures 2 and 17 for which I extend my apologies to my colleagues. Finally I want to thank Professor Suresh .C. Tonwar for the excellent hospitality and organization under difficult circumstances. This work was supported in part by the National Science Foundation.

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