THE PUZZLE OF ULTRA HIGH ENERGY COSMIC RAYS AND THE PIERRE AUGER PROJECT

FRANÇOIS MONTANET
FERMILAB, IL 60510, USA

On Behalf of the Pierre Auger Collaboration.

A handful of cosmic rays with macroscopic energies exceeding $10^{20}$ eV have been detected during the last 40 years. The origin of such events are yet to be explained. There is a whole variety of theoretical explanations ranging from conventional shock acceleration to hypothetical heavy relics of the early universe. The existence of events above the predicted GZK cutoff in the energy spectrum at $\approx 7 \times 10^{19}$ eV could be a hint of new physics. On the other hand, we are entering a new experimental era: large size detectors such as the Pierre Auger Observatory will provide the required statistics for detailed spectral, anisotropy and composition studies of these high energy particles. This will shed a new light on very early universe and on the origin of the cosmic rays. We give here a quick overview of the theoretical and experimental situation and present the status of the Pierre Auger project in more detail.

1 Introduction

After a century of discoveries, adventurous research and detailed studies, the very origin of cosmic rays is still a mystery.

Their energy spectrum which extends over more than ten decades from the GeV scale up to $10^{20}$ eV can be modelled by an almost featureless power law with only a slight breaks in the slope called “the knee” at $10^{15.5}$ eV, at $10^{17.8}$ eV (the second knee) and the “ankle” at $10^{19}$ eV. In the following, we will concentrate on the higher part of this spectrum, namely energies above $10^{19}$ eV which we will call Ultra High Energies (UHE) and energies above $10^{20}$ eV which will be called Extremely High Energies (EHE).

If the rates and the spectrum are rather well measured up to the highest energies, we are still unable to locate the sources of these particles. This is mainly because Galactic and inter-galactic magnetic fields are strong enough to scramble their path except at the highest energies. Thus almost nothing certain is known about their origin on the entire spectrum.

Up to GeV energies, acceleration mechanisms induced by solar flares can explain the measured flux of protons with rather well measured contribution from nuclei such as carbon, oxygen and iron. At and above the knee, one has to quit using satellites and airborne equipments whose acceptances are too small and use ground based techniques.

Therefore, above $10^{15}$eV all the measurements are indirect. The high energy particle enters in the atmosphere and interacts with the air molecules initiating a cascade of particles forming an Extensive Air Shower (EAS). The latter can be detected by a surface array of detectors or by optical telescopes sensitive to the fluorescence light emitted by nitrogen molecules excited by the shower ionizing particles.

Cosmic rays up to the knee are believed to be of galactic origin and to be produced in diffusive shock acceleration processes in the expansion shell of recent supernovae. One should stress that if this model is viable, no direct evidence of hadron acceleration phenomenon has

\[pascos-montanet:\]
been seen so far and most of the high energy sources observed with gamma rays telescopes or X-ray imagers are considered to be pure electron and positron accelerators. The knee feature of the energy spectrum is usually explained either by energy limited confinement by the Galactic magnetic field and/or by different high energy cutoff for different species of charged particles in the acceleration process.

Whether Galactic conventional sources are indeed able to accelerate particles up to the ankle energy is questionable and there is still much debate on the origin of cosmic rays observed above the knee.

At the highest energies, in our Galaxy, magnetic confinement is presumably too weak to explain the rates observed. One is thus tempted to interpret the breaks or the dip in the slope and a possible change from heavier to light in the chemical composition between $10^{18}$ eV and $10^{19}$ eV as an evidence for the emergence of a different kind of cosmic rays above the ankle, i.e. extragalactic protons. Extra galactic sources such as powerful radio galaxies (AGN’s jets hot spots) are proposed as potential accelerators up to energies of $10^{18}$ eV, possibly $10^{19}$ eV. However, most models need to have their parameters pushed above realistic limits in order to account for energies higher than this. Of course, even if the requirements of energetics are solved, one has to consider cosmological sources distribution and one has to take into account the propagation of protons or nuclei over cosmological distances.

At energies above $\approx 7 \times 10^{19}$, protons and nuclei will lose energy during their propagation due to the Griesen-Zatsepin-Kuzmin (GZK) effect, namely they will undergo pion photoproduction and photo-disintegration processes when interacting with the cosmic microwave and infrared background. This limits suddenly our horizon to distances $\lesssim 50$Mpc for any source of EHECR nucleons. There are no or very few conventional astrophysical sources considered by the experts as being able to accelerate particles at EHE energies in the GZK sphere. Furthermore, at such energies, the bending effect of the galactic and extragalactic magnetic fields are quite weak. Thus, the reconstructed incident direction should point toward the sources within a few degrees and, contrary to lower energy cosmic rays, EHECR can be used for point source astronomy.

The existence of the few tens of events observed so far above the GZK cutoff and the difficulties in explaining them in a conventional way have led to a proliferation of more exotic ideas, ranging from new interactions to early universe relics decays. In the case of the decay of heavy meta-stable particles, the energy is not provided by an acceleration mechanisms. To distinguish between the two classes of models, it is fashionable to call the conventional acceleration scheme “Bottom-Up” and the decay scheme “Top-Down”.

The upcoming much larger experiments will hopefully overcome the present frustrating situation and will provide enough information to solve this puzzle.

2 Phenomenology of UHECR

2.1 Propagation

Because of the interactions with the 2.7 Kelvin cosmic microwave background radiation (CMB), the attenuation length of EHECR is limited to less than about 50 Mpc.
threshold energy for pion photo-production is given by

\[ E_{\text{th}} = \frac{m_\pi (m_N + m_\pi/2)}{\varepsilon_{\text{CMB}}} \approx 6.8 \times 10^{19} \left( \frac{\varepsilon_{\text{CMB}}}{10^{-3} \text{eV}} \right)^{-1} \text{eV}, \]

where \( \varepsilon_{\text{CMB}} \sim 10^{-3} \text{eV} \) is a typical CMB photon energy. For energies higher than this threshold, the nucleon will undergo significant energy loss on a length scale of \( \Lambda_{\pi} \approx 1/(\sigma_\pi n_{\text{CMB}}) \approx 20 \text{ Mpc} \), where \( n_{\text{CMB}} \approx 420 \text{ cm}^{-3} \) is the number density of CMB photons, and \( \sigma_\pi \sim 10^{-25} \text{ cm}^2 \) is the pion production cross section. Nuclei will mostly be affected by photo-disintegration on similar length scales and threshold, gamma-rays will pair produce electron and positron but with a much lower energy threshold. Fig. 1 shows the attenuation length as function of the energy for proton, iron and gamma-rays.

As our horizon shrinks dramatically for energies above \( 7 \times 10^{19} \text{eV} \) and if the sources of cosmic rays follow a cosmological distribution, one would expect a sudden cutoff in the energy spectrum. This is the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff.

Another effect to be taken into account when studying the propagation of UHECR is their deflection by magnetic fields if they carry an electrical charge. These fields and especially extra galactic fields (EGMF) are poorly known in terms of strength and structure. Upper limits established from frequency dependent Faraday rotation of the polarization of radio emission from distant sources favor values of the order of \( 10^{-10} \) Gauss. Typical length of coherence of the order of 1 Mpc are generally assumed, i.e. much smaller than the Larmor radius of an EHECR of charge 1 in a nG field. The corresponding deflections are of the order of a few degrees, the spread of the arrival time distribution being measured in centuries.
2.2 The Bottom-Up acceleration models

In the case of diffusive shock acceleration in an astrophysical object, an estimate of the maximal energy that can be achieved is given by the requirement that the size $R$ of the shock be larger than the gyroradius $r_g \simeq E/(ZeB)$ of the particle of charge $Ze$ and energy $E$ in a magnetic field $B$:

$$E \lesssim Z \left( \frac{R}{\text{kpc}} \right) \left( \frac{B}{\mu \text{G}} \right) 10^{18}\text{eV}, \quad (2)$$

where $B$ is measured in micro Gauss ($\mu\text{G}$) and $R$ in kilo parsecs. Eq. (2) is an optimistic estimate since it neglects the finite lifetime of the accelerator and energy losses due to interactions with the ambient environment such as synchrotron radiation in the magnetic field and production of secondary particles. This limit is illustrated by the well known “Hillas” plot (fig.2). Very few source candidates escape this maximal energy constrain.

In our own Galaxy, potential stellar scale size sources of EHE iron nuclei are pulsars with ms period and very intense magnetic fields $\geq 10^{14}\text{G}$, but the accelerated iron nuclei have to survive large energy losses in the dense electromagnetic environment of the pulsar. Other interesting but even more speculative suggestions have been made. A clear signature for Galactic sources is a strong large scale anisotropy correlated with the Galactic structure, a feature already excluded by the data.

Extra galactic sources include AGN accretion disks, hot spots in radio galaxies jets, shock waves associated with large scale structure formation and gamma-ray bursts. Strong energy losses in the intense radiation field moderate the maximal energy in AGN.
core models and they are unlikely to reach EHE energies. The most promising objects are the “hot spots” in the jets of radio galaxies. There the environment is tenuous enough and mG fields extending over kpc scales fulfill the requirement of eq. (2). It remains that such objects are rare and most probably absent in the GZK sphere \(^7\).

Gamma-ray bursts (GRB) are not yet fully understood astrophysical phenomena, emitting up to \(\sim 10^{54}\) ergs in gamma-rays (depending on the unknown amount of beaming) within a few seconds. Shock induced by the fireball explosion could accelerate particles up to EHE energies \(^9\). They occur with a rate of about one burst per 100 years within a GZK distance and therefore, if GRBs are to explain the observed rate of EHECRs, they have to emit at least as much energy in the form of EHECRs as in MeV gamma-rays \(^10\).

The experimental signature for all these bottom-up sources are:
- A correlation with matter distribution within 100Mpc,
- a power law spectrum,
- a visible GZK cutoff,
- a proton dominated chemical composition,
- for GRBs, a time dependant narrow peaked spectra, time-energy correlations, and EHE neutrinos.

2.3 Avoiding the GZK paradox

Since, as we will discuss later, the data contradict the existence of a cutoff, one is left with a somewhat paradoxical situation. Many ways to avoid the GZK contradiction have been proposed, not necessarily invoking new physics. We do not have the space here to describe them, the reader may find relevant the references at the end of the article.\(^11,12,13\).

An interesting model presented at this conference by Haim Goldberg is based on a single source (Cen A), responsible for the entire UHECR flux scattered by strong magnetic fields.\(^14\)

Bottom-up or acceleration scenarios have apparent intrinsic difficulties and this motivated the proposal of the “top-down” scenarii.

2.4 Top-Down scenarii

In top-down models, UHECRs are produced in the decay products of massive “X” particles produced by physical processes in the early Universe. These particles are naturally associated with the grand unification (GUT) mass scale \(\sim 10^{16}\) GeV, i.e. 5 orders of magnitude above EHE energies. It is improbable that these X-particles are themselves dark matter relics as the theory predicts that they should be very short lived particles. One needs a mechanism to continuously produce them if their decays are to give rise to UHECRs. A way out is to invoke their emission in the annihilation or the collapse of topological defects such as cosmic strings and monopoles. These are a natural consequence of cosmological phase transitions that could have occurred in the post-inflation Universe reheating phase at temperatures close to the GUT scale.

The X particles decay into jets of particles and the injection spectrum is therefore a rather hard fragmentation-type shape with a upper limit fixed by the GUT scale. It is reprocessed by interactions with the CMB and IR photons and magnetic fields \(^2,17\). A unique characteristic is that gamma-rays and neutrinos will dominate the proton flux, and of course, no nuclei are expected. One should stress that predictions on the flux of EHECR...
from topological default models are very uncertain and that a whole range of values have been proposed.

2.5 New Primary Particles, New Interactions

Another way around the limited range of EHECR is to propose primary particles not interacting with the CMB photons. The most obvious candidate is the neutrino but unfortunately observed events do not favor very penetrating particles. Within the Standard Model, $\sigma_{\nu N}$ is about five orders of magnitude too small to explain the observed events. On the other hand, limits imposed by unitarity are relatively weak and theoretical possibilities to increase significantly the neutrino cross section have been proposed.\textsuperscript{18,19} Therefore, neutrino induced air showers above $10^{15}$ eV could provide a directly probe of new physics beyond the EW scale.

A more speculative idea is to propose a neutral long lived (and yet undiscovered) particle with a mass much higher than the nucleon and thus with a much higher interaction threshold according to Eq. (1). Such particles are predicted in the frame of supersymmetric models.\textsuperscript{20} Other candidates immune to the GZK degradation are magnetic monopoles\textsuperscript{21} and superconducting string loops\textsuperscript{22}. Both atmospheric penetration depth and angular distributions are already setting some limits on such primary particles as EHECR.

3 Detecting the EHECR

At energies above the “knee”, there are two techniques applicable to the detection of UHECR. The first uses the fact that numerous particles produced in the late development of the shower reach the ground. An array of detectors spread over a large area can sample these particles, measuring their densities and distribution in time. From this sampling of the lateral development of the shower particles, one can reconstruct the direction, the energy and possibly the identity of the primary cosmic ray. The second technique looks directly at the longitudinal development of the EAS by detecting the fluorescence light produced by the interactions of the charged secondaries.

3.1 The Extensive Air Showers

The atmosphere acts on a UHECR as a variable density calorimeter with a total vertical thickness of 26 radiation lengths and about 11 interaction lengths. At sea level the number of secondaries reaching ground level (with energies $> 200$ keV) is about $3 \times 10^{10}$ particles, of which 99% are few MeV photons and $e^+/e^-$. The remaining 1% consist mostly of muons with an average energy of 1 GeV, a few GeV pions, neutrinos and baryons in negligible amount.

The shower lateral development extends much farther than the Molière radius ($\sim 70$ m): at 1 km from the shower axis, the average densities of photons/electrons/muons are $30/2/1$ per m$^2$, for a $10^{19}$ eV EAS. The EAS has a longitudinal development usually parameterized by the analytic Gaisser-Hillas function giving the number of the ionizing electrons $N_e$ as a function of atmospheric depth $x$:

$$N_e(x) = N_{\text{max}} \left( \frac{x - x_0}{X_{\text{max}} - x_0} \right)^{(X_{\text{max}} - x_0)/\lambda} e^{(X_{\text{max}} - x)/\lambda}$$

(3)
where $\lambda = 70 \text{ g/cm}^2$, $x_0$ is the depth at which the first interaction occurs, and $X_{\text{max}}$ the position of the shower maximum. The total energy of the shower is proportional to the integral of this function, knowing that the average energy loss per particle is 2.2 MeV/g cm$^{-2}$.

The maximum size of a $10^{19}$ eV proton shower is reached at an atmospheric depth of 830 g/cm$^2$ (or an altitude of about 1800 meters) and contains about $7 \times 10^9$ electrons which produce the fluorescence light detected with the Fly’s Eye telescopes (see fig.3(a)).

Showers initiated by heavier nuclei can conveniently be described by making use of a superposition principle: a heavy nucleus of mass number $A$ and energy $E$ can be in a first approximation considered as a superposition of $A$ showers initiated by nucleons each with an energy of $E/A$. It will therefore be less penetrating than a nucleon of energy $E$ (roughly 100 g/cm$^2$ higher in the atmosphere for iron w.r.t proton). A fluorescence detector which measures the shower development will thus be sensitive to the nature of the primary particle. Unfortunately, as one may see in fig.3(b)), physical fluctuations of the interaction point and of the shower development blur this ideal image. As an example, at $10^{19}$ eV the typical fluctuation on the $X_{\text{max}}$ position is 50 g/cm$^2$.

There are also two indirect consequences of this which are used by ground arrays to separate heavy from light nuclei (and from photons): in the case of a heavy nucleus, the shower is richer in muons (in proportion to the electromagnetic component) and these muons (which are produced higher up in the EAS development) arrive earlier.

For a photon shower the proportion of muons will be even smaller. At EHE energies another physical process has to be taken into account: for the air of the upper atmosphere, this is the energy regime for which the cross section of photons and electrons on nucleus is reduced by the Landau-Pomeranchuk-Migdal (LPM) effect. A $10^{20}$ eV photon will develop an EAS very deep in the atmosphere, yielding less than $10^9$ particles at ground level. Such a shower would have an extension of only a few km$^2$.

These effects are studied through heavy use of EAS Monte Carlo programs, used together with models for the high energy hadronic interactions. It is a legitimate question to ask if, at center of mass energies much above any accelerator based measurements, the extrapolations which are used in modelling the physical processes are valid. The models are indeed constrained by existing lower energy data, such as those for HERA or through comparison with detailed $10^{16}$ eV EAS measurements like those from the KASKADE ground array.

One should also stress that, when simulating a shower, these extrapolations to unknown physics regions are only used for the first few interactions. The main shower parameters, such as the reconstructed direction and energy of the primary particle, do not depend strongly on the chosen model. The identification of the primary is more problematic and large physical fluctuations make an unambiguous identification difficult.

### 3.2 The fluorescence technique

The idea of using the fluorescence light emitted by EAS in the atmosphere was first proposed in the early sixties. Charged particles, mostly electrons and positrons that carry $\gtrsim 90\%$ of the EAS energy, excite the nitrogen atoms of the atmosphere which then emit fluorescence light isotropically. It can then be detected by photo-multipliers. Only less than a percent of the energy deposited is transferred to fluorescence emission. Therefore this technique can only be applied to EHE energies, the weakness of the emission being compensated by
(a) Longitudinal profile of the $3 \times 10^{20}$ eV event, the highest-energy event ever detected, observed by the Fly’s Eye I detector.

(b) The vertical development of $10^{19}$ eV showers of proton, iron, and gamma-ray primaries. Ten showers are drawn (CORIKA+QGSJET simulation). (from Heck)

Figure 3.

the huge number of particles in the shower (eq.3). Observations can only be done on clear moonless nights which results in an average 10% duty cycle. Under favorable atmospheric conditions an EHECR shower can be detected at distances as large as 20 km (about two attenuation lengths).

The first successful detectors based on these ideas were built by a group of the University of Utah, under the name of “Fly’s Eyes”. The detector sees the shower as a few tens of Watts light source moving at the speed of light along the shower axis. The detector consists of a multi-pixel camera composed of photo-multipliers at the focal plane of a set of spherical mirrors. Each phototube sees a small portion of the sky (typically 1° square). From the pattern of pixels hit by the fluorescence photons, one can reconstruct the plane defined by the shower axis and the detector position with a precision better than one degree. When two telescopes installed a few km apart are used in stereo mode, the intersection of the two planes reconstructed gives the incident direction with good precision. In the mono mode, one has to rely on the the time of arrival of the photons on the tubes to fully determine the shower position. Ultimately, in the hybrid mode, i.e. simultaneous detection of the EAS with a fluorescence telescope and a ground array, the good measurement of the position of the shower axis by the ground array allow a precise determination of all the shower parameters. For $10^{20}$ eV showers, a precision of 0.5° can then be reached.

The fluorescence technique provide calorimetric measurement of the energy of the incident cosmic ray with continuous longitudinal sampling. The amount of fluorescence light emitted is proportional to the number of charged particles in the shower (eq.3). In practice...
several effects have to be taken into account to properly convert the detected fluorescence signal into the primary CR energy. These include the subtraction of the direct or diffused Cerenkov light, the Rayleigh and Mie scattering, the altitude and atmospheric conditions dependant attenuation length, the hidden part of the shower energy transported by neutral particles or lost by hadrons interaction or penetrating muons. All these effects contribute to the systematic errors in the energy measurement which needs sophisticated monitoring and calibration techniques. The resulting energy resolution depends on the EAS energy but also on the detection mode (mono, stereo or hybrid). The HiRes detector should have a resolution of 25% or better above $3 \times 10^{19}$ eV in the mono mode and this improves significantly in the stereo. A hybrid detector could reaches 5% median relative error.

The measurement of $X_{\text{max}}$ is used by fluorescence detectors to provide some identification of the primary cosmic rays but because of the huge fluctuations in the process, this technique used alone cannot define the primary composition on a shower-by-shower basis. Therefore, one must look for statistical means of studying the chemical composition. In the case of hybrid detection method a multi-variable analysis becomes possible and give promising results.

3.3 The ground array technique

A ground array consists of particle detectors, scintillator or Cerenkov detectors, distributed as a more or less regular matrix over some surface. The spacing and the total area are optimized for an energy range (smaller spacing for lower energies and large areas for higher energies lower fluxes). The largest array so far is the 100 km$^2$ AGASA array which is appropriate to detect $10^{20}$ eV events at a rate of about one event per year.

These detectors count the number of secondary particles which cross them as a function of time. The incident cosmic ray direction and energy are measured by assuming that the shower has an axial symmetry. This assumption is valid for not too large zenith angles (usually $\theta < 60^\circ$). At larger angles geomagnetic fields deflection on low energy secondaries has to be taken into account.

The particle densities measured by the ground stations are fitted with an analytical “lateral distribution function” or LDF, which shape depends on the type of detector used and is taken from shower theory and Monte Carlo studies at a given energy range. A first estimate of the zenith angle is obtained and an estimator of the primary cosmic ray energy is extracted from the fit. It has been found that the particle density at some distance from the shower core is a rather good estimator of the energy. This parameter is known as $\rho_{600}$ or $\rho_{1000}$. Because of variations in the primary interaction point, there are large fluctuations in the ground densities close to the core. At the same time, the statistical fluctuations in the measured densities are important at large distances where the densities are low. Monte Carlo studies show that somewhere in between, the overall fluctuation reaches a minimum. This happens to be at 600 m from the core, a value that slowly increases with the energy. In the EHECR range, a more appropriate density is $\rho_{1000}$. The primary energy is related to $\rho$ by a quasi-linear relation.

The spacing between the stations determines the threshold energy for a vertical shower: the 500 m spacing of the Haverah Park triggering stations corresponds to a threshold of a few $10^{16}$ eV, while the 1.5 km separation of the Auger Observatory stations makes this array almost 100% efficient for energies above $10^{19}$ eV.
In a ground array, the primary cosmic ray’s identity is reflected in the proportion of muons among the secondaries at ground level, by the rise time of the muons arrival time and by the particle front curvature.

3.4 Detecting neutrinos

A promising way of detecting ultra-high energy neutrinos is look for deeply penetrating large zenith angles ($\gtrsim 60^\circ$) or horizontal air showers. At these large angles, hadronic showers have traversed the equivalent of 2 to 3 times the depth of the vertical atmosphere and their electromagnetic component has extinguished far away from the detector. Only very high energy core produced muons survive past 2 equivalent vertical atmospheres. Therefore the shape a hadronic (background in that case) shower front is very flat and very prompt in time. In contrast, a neutrino shower appears pretty much as a “normal” shower. It is therefore straightforward to distinguish neutrino induced events from background hadronic showers.

Tau neutrinos could be as abundant as other species if full flavor mixing is confirmed. It has been realized that in the range $10^{17}$ eV to $10^{20}$ eV, even very low $\nu_\tau$ fluxes could be detected very efficiently by ground array detectors by looking at the interaction in the earth crust of quasi horizontal $\nu_\tau$ inducing an horizontal cascades at the detector.

4 Past and present experiments and Big events

We will very briefly summarize the properties of the UHECR events detected so far. The reader will find much more information and discussion in excellent recent reviews of this subject.

The existing data set, which is summarized in table1, consist of about 15 EHE events. it has been collected over the last 40 years by experimental setup starting back in the sixties with the Volcano Ranch experiment, followed by the Haverah Park, which developed the ground array techniques. Then came the fluorescence techniques with the Fly’s Eye, replaced recently by the HiRes telescopes. The largest still operating ground array the AGASA setup (Akeno, Japan) which covers about 100 km$^2$. A detailed description and comparison of these detectors and their data is found in M. Nagano and A.A. Watson.

The total exposure of past and present experiments is of the order of 4000 km$^2$ sr yr. The expected EHE flux is less than 1 particle per km$^2$ per sr per century! Clearly more statistics is required to reconstruct the shape of the spectrum, look for point sources, study possible anisotropy, and try to reveal the chemical composition of EHECR. This will only be possible with detectors of much larger exposure rate, typically a few $10^4$ km$^2$ sr, ensuring hundredth of events per year above $10^{20}$ eV and 10000 above ten thousand above $10^{19}$ eV.

4.1 Energy spectrum

The observed supra-GZK events were of course submitted to very detail studies. Their flux is extremely low, it falls very steeply with energy and the energy determination is not free of systematic uncertainties. We will not discuss possible experimental bias here in detail. However, one should stress that it would require huge effects or totaly unexpected physics to shift down the EHE events to energies below the GZK cutoff.
Table 1. Existing or past experiments contributing to the EHE events data set, their total exposure and number of events detected resp. above $10^{19}$ eV, $10^{19.6}$ eV and $10^{20}$ eV.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Total exposure in km$^2$ sr yr</th>
<th>No. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{19}$ eV</td>
<td>$10^{19.6}$ eV</td>
</tr>
<tr>
<td>Volcano Ranch</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>Haverah Park</td>
<td>135</td>
<td>230</td>
</tr>
<tr>
<td>Yakutsk</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Fly’s Eye (mono)</td>
<td>412</td>
<td>825</td>
</tr>
<tr>
<td>Fly’s Eye (stereo)</td>
<td>130</td>
<td>145</td>
</tr>
<tr>
<td>HiRes1 mono (97-99)*</td>
<td>970</td>
<td>1090</td>
</tr>
<tr>
<td>AGASA (may 2000)</td>
<td>1270</td>
<td>1270</td>
</tr>
</tbody>
</table>

* These data are still considered as preliminary and were published in [50].
** AGASA is now reporting data with a zenith angle cut at 60° instead of 45°. This increases the acceptance and exposure by a factor 1.5. The total number of events above $10^{20}$ eV with $\theta < 60^\circ$ is now 15 events.

(a) Highest energy region of the cosmic ray spectrum as observed by the AGASA detector. The figures near the data points indicate the number of events in the corresponding energy bin. The arrows show 90% confidence level upper limits. The dashed line is the expected spectrum if the sources were cosmologically distributed.

(b) Arrival directions of cosmic rays with energies above $10^{19}$ eV on the equatorial coordinates as measured by the AGASA detector. Open circles, and open squares represent cosmic rays with energies of $(4 - 10) \times 10^{19}$ eV, and $\geq 10^{20}$ eV, respectively. The galactic and supergalactic planes are shown by the red and blue curves. Large circles indicate event clusters within 2.5°. The shaded regions are those invisible to the AGASA detector.

Figure 4.
Figure 4(a) is a zoom on the highest energy range of the spectrum where the AGASA data alone are displayed, compared to the expected spectrum if the sources were cosmologically distributed and have an injection spectrum following a $E^{-3}$ power law. Many similar comparisons of the data to different models have been done, assuming local sources over-densities, different EGMF assumptions or harder injection spectra. Most of these studies conclude that for conventional assumptions, there is no way to reconcile the existing data and the predicted supra-GZK fluxes.

4.2 Anisotropy

The EHE sky maps have been thoroughly studied for possible anisotropy and angular correlation with the distributions of astrophysical matter, like the Galactic disk, the supergalactic plane on a larger scale or know potential sources within a GZK distance. The AGASA experiment did such an analysis for there events above $4 \times 10^{19}$ eV (see fig.4(b)). They found no deviation with respect to a uniform right ascension distribution. Note that both AGASA and Fly’s Eye saw some significant galactic plane enhancement at a few percent level at lower energies (around $10^{18}$ eV).

If at large angular scale no significant departure from isotropy is observed, a possibly significant clustering of arrival directions on degree scales seems to be present in the data. This has trigger a lot of excitement as, give the limited statistics, it might be the clue for a few nearby point like sources.

These clusters or multiplets are defined as a group of events whose error boxes (2.5° circles) overlap. Figure 4(b) shows that, in the AGASA $E > 4 \times 10^{19}$ eV data only, 6 doublets and one triplet events are identified. The chance probability of having as many multiplets in a uniform distribution is about 1%. The chance probability of the triplet event itself is also $\sim$1%. Note that this strongly depends on the assumed experimental errors. Obviously, searches for astrophysical objects with position correlated with these clusters were carried out and produced a few candidates.

Clearly the present situation is affected by a frustrating lack of statistics. Hopefully we should soon learn more from future large aperture detectors, the first of which is the Pierre Auger observatory.

5 Pierre Auger Observatory: a hybrid detector

The Auger Observatory represents a major step forward: almost two orders of magnitude in exposure rate with respect existing experiments, a complete sky coverage with two sites in each hemisphere, a design based on the “hybrid” detection mode (EAS simultaneously observed by a ground array and a fluorescence detector).

The Observatory will be covering two sites, respectively in the southern (Pampa Amarilla, province of Mendoza, Argentina) and northern (Millard County, Utah, USA) hemispheres. The southern hemisphere detector, whose installation is progressing, will look at a yet poorly covered part of the sky in which the direction of the center of our galaxy is visible.

On each site, the ground array will cover a surface of 3000 km$^2$. Each site consist of 1600 “stations” spaced 1.5 km apart from each other on a regular grid. The corresponding

\footnote{Named after the French physicist Pierre Auger who discovered the phenomenon of EAS.}
limiting aperture will be $2 \times 7350 \text{km}^2 \cdot \text{sr}$ so as to provide a statistics of a few tens of expected events per year above $10^{20} \text{eV}$. The detector is designed to be fully efficient for showers with energies of $10^{19} \text{eV}$ and above, with a duty-cycle of 100%. This will make the link with the part of the energy spectrum well explored by presently operating detectors, AGASA and HiRes. The energy threshold is defined by the 1.5 km spacing of the detector stations: a $10^{19} \text{eV}$ vertical shower will hit on average 6 stations which is enough to fully reconstruct the EAS.

Each station is a cylindrical tank of 10 m$^2$ surface and 1.2 m height. The tanks are filled with purified water in which the secondary particles from the EAS produce light by Cerenkov radiation. The light is reflected and diffused by an internal coating and detected by three photo-multipliers installed on the top. Flash-ADCs cycling at a rate of 40 MHz record the pulse heights as a function of time. With such a system, the separation of the muons from the electromagnetic component of the shower becomes reasonably good.

For obvious reasons, each station has to work in a stand-alone mode: they are powered by solar panels and batteries, and the communication with the central station where the data-taking system is installed is done by radio telecommunication techniques.

The Auger observatories are designed to run part of the time in the hybrid mode. The ground array is thus over viewed by a set of fluorescence telescopes. pixels (photo-multipliers) with a field of view of 1.5°. A telescope is a camera with 440 pixels (each with a field of view of 1.5°) installed at the focal plane of a set of mirrors. Each telescope sees an angle of about 30 × 30 degrees. Three eyes (6 or 7 telescopes each) will be installed at the periphery of the array and one (12 telescopes) in the middle, in order for the whole array to be visible by at least one of the telescopes.

In the hybrid mode (~10% of the time), the detector is expected to have energy reso-
olution of 13% (1 σ) at 10^{18} eV improving to 5.5% at 10^{20} eV, and an angular resolution of about 0.5°. For the ground array alone these numbers become 10% and 1°, again for E > 10^{20} eV.

Estimating detected event rates is a risky business because above 10^{20} eV the rates essentially not known. However, extrapolating from the AGASA measurement and for a total aperture of 14350 km²sr (both sites), the Auger Observatory should detect of the order of 5000 events above 10^{19} eV and of a 50 to 100 events above 10^{20} eV every year, 10% of those in hybrid mode.

The installation of the southern site is now well underway. By the time I am writing this paper (may 2001), a first set of 40 stations of the ground array have been install and started to communicate with the central data acquisition system. The first fluorescence building is now equipped with 2 fluorescence telescopes. First high energy showers candidates have already been detected by the fluorescence detector after a few hours of operation! This ensemble completes the “engineering array” whose role is to validate the design and prepare the production of the complete observatory.

6 Conclusions

Almost 40 years after their first observation, EHECR are still a puzzle. It seems that no conventional explanation will be likely to survive experimental facts. This puzzle might actually be a clue that Nature is giving us on something beyond our present understanding. We are not short of ideas, but we do are short of data. Statistics and better experimental handles should enable us to reconstruct the shape of the cosmic ray spectrum above the cutoff, to locate the sources in the sky, and to study the cosmic ray chemical composition. We are entering this new experimental era with the Pierre Auger Observatory.

Acknowledgements

This work was supported in part by DOE and URA at FERMILAB. I am grateful to the conference organizers for inviting me and to P. Frampton his hospitality. I have made extensive use, for this article, of the work produced by collaborators of the Pierre Auger project and I would like to thank them for this.

References

1. K. Greisen, Phys. Rev. Lett. 16, 748 (1966);  
15. N. Hayashida et al., *Phys. Rev. Lett.* **77**, 1000 (1996);
and references therein.
   P. Billoir, “Neutrino capabilities of the AUGER detector”, 8th International Workshop
   on Neutrino Telescopes, Venice, (1999);
41. for a summary of the data situation and experimental issues see, e.g., S. Yoshida,
   H. Dai, J. Phys. G 24, 905 (1998);
   X. Bertou, M. Boratav, A. Letessier-Selvon, Int. J. Mod. Phys. A15, 2181 (2000);
   M. Nagano, A. A. Watson, Rev. Mod. Phys. 72, 689 (2000), and references therein.
   (2000).
48. D. B. Cline, F. W. Stecker, OWL/AirWatch science white paper, e-print astro-
   ph/0003459; see also http://lheawww.gsfc.nasa.gov/docs/gamcosray/hecr/OWL/.
   ph/0009466].
55. N. Hayashida et al. [AGASA Collaboration], astro-ph/9906056.
56. T. Takeda [AGASA Collaboration], Prepared for 26th International Cosmic Ray Ray
   Conference (ICRC 99), Salt Lake City, Utah, 17-25 Aug 1999.