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Astrophysics of Extremely High Energy Cosmic Rays: Observational Status and New Projects

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Recent results on primary cosmic rays of energies above 1×10^{19} eV observed by the Akeno Giant Air Shower Array (AGASA) are summarized, together with the results of previous experiments by other groups. The implications of these results for their origin and propagation through the intergalactic space are discussed. The next generation experiments, the HiRes Detector, the Telescope Array Project and the Auger Project, are now under preparation. Their present status is briefly presented.

1. INTRODUCTION

The energy spectrum of primary cosmic rays extends from 10^9eV to 10^{20}eV almost continuously over the ten decades with small changes in slope in a power-law energy spectrum. The energies where these slope changes occur are called as *knee* (around $10^{15.5}$eV) and *ankle* (around 10^{19}eV). The fluxes above $\geq 10^9$eV, $\geq 10^{16}$eV and $\geq 10^{20}$eV are $\sim 1/\text{cm}^2\text{sec}$, $\sim 1/\text{m}^2\text{year}$ and $\sim 1/\text{km}^2\text{century}$, respectively.

The origin of cosmic rays below the *knee* is most likely due to diffusive shock acceleration in the supernova blast wave [1]. Around and beyond the *knee* there are many proposals for acceleration mechanisms, however, there is no consensus on their origin. Reliable determination of energy spectra of different nuclear species is indispensable to discriminate among various models. Any way it is most crucial that energy spectra below and beyond the *knee* must match with each other smoothly around the *knee* if different mechanisms and different type of natural accelerators are invoked to understand the origin.

In the highest energy region, distinctive features in the energy spectrum and arrival direction distribution are expected. If the cosmic rays are of extragalactic origin, photopion production between cosmic rays and primordial microwave background photons becomes important at energies above 6 $\times 10^{19}$eV with a mean free path of about 6Mpc. Therefore a cutoff in the spectrum may be observed around several times 10^{19}eV even if the primary cosmic ray energy spectrum extends beyond 10^{20}eV. This is called as the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2].

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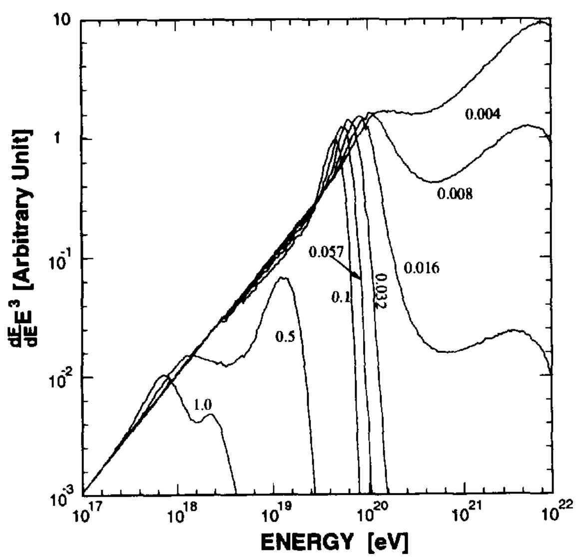

Figure 1. Expected energy spectra for a single source at several distances corresponding to redshifts from 0.004 to 1. The primary spectra are assumed to have a power law spectrum with a spectrum index of 2.0 without any cut-off.

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Table 1
Sites of six EHECR experiments

Experiment	begin	end/status	longitude	latitude	altitude	note
Volcano Ranch	1959	1963	35°09'N	106°47'W	834 g/cm^2	442m span
	1972	1974				884m span
SUGAR	1968	1979	30°32'S	149°43'E	1020g/cm^2	muon detector
Haverah Park	1968	1986	53°58'N	1°38'W	1020g/cm^2	water tank
Yakutsk	1972	in operation	62°'N	130°'E	1020g/cm^2	scintillator muon detector
Fly's Eye	1981	1992	40°'N	113°'W	869g/cm^2	air fluorescence monocular
AGASA	1990	in operation	38°47'N	138°30'E	920g/cm^2	scintillator muon detector

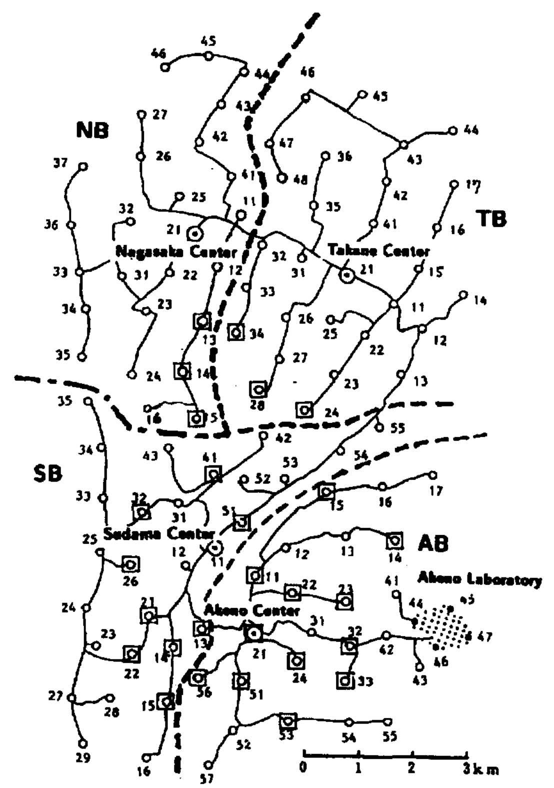


Figure 2. Schematic view of the AGASA. Open circles and squares represent the surface detectors and the shielded detectors, respectively. Solid lines show the routes of the optical fibers for a data communication network. Compact array of southeast corner is called 1km^2 (A1).

An example of the results obtained from Monte Carlo simulation of propagation of protons in the intergalactic space is shown in figure 1 [3]. It is seen that the observed spectrum is modified according to the distance to the sources. In this scenario, the expected arrival direction distribution of the extremely high energy cosmic rays (EHECR) may be quite isotropic.

On the other hand, if they are galactic origin, the expected arrival direction distribution of cosmic rays is no more isotropic, since the gyroradius of protons of energy above 10^{19}eV exceeds the thickness of the galactic disc. Therefore a study of correlations of the extremely high energy cosmic rays with the galactic structure and/or with the large scale structure of galaxies is very important.

2. RECENT EXPERIMENTAL RESULTS

2.1. Experiments

The first experiment on extremely high energy cosmic rays was carried out by Linsley in the United States in 1960's. Later, experiments have been performed at Haverah Park in England, Yakutsk in Russia, Sydney in Australia and Dugway in USA. We started the Akeno Air Shower Experiment in 1979 with an array covering 1km^2 area and expanded the array to Giant Air Shower Array (AGASA) of 100km^2 area in 1990.

The experimental sites and their operational period of highest energy cosmic rays made so far are listed in Table 1. Volcano Ranch, Haverah Park, SUGAR and Fly's Eye experiments stopped their operation and the Yakutsk array has been re-arranged to a smaller area than the earlier array, in order to investigate around 10^{19}eV energy region in detail. Therefore only AGASA is now in operation around the GZK cutoff energy region and I would like to talk today mainly on results from AGASA experiment.

The schematic view of the AGASA is shown in figure 2 [5]. The AGASA consists of 111 scintillation detectors of $2.2m^2$ area each, which are arranged with inter-detector spacing of about 1km. The two-way communication between the detectors and the central station of each branch for data transmission is carried out through two optical fiber cables. The triggering requirement is more than 5 fold coincidences of neighboring detectors.

2.2. Energy Spectrum

The Akeno energy spectrum covers five decades in energy and twenty decades in flux and is shown by open circles in figure 3, along with the energy spectrum determined by the direct observations [7–9] and the results determined at 4300 m a.s.l. [6].

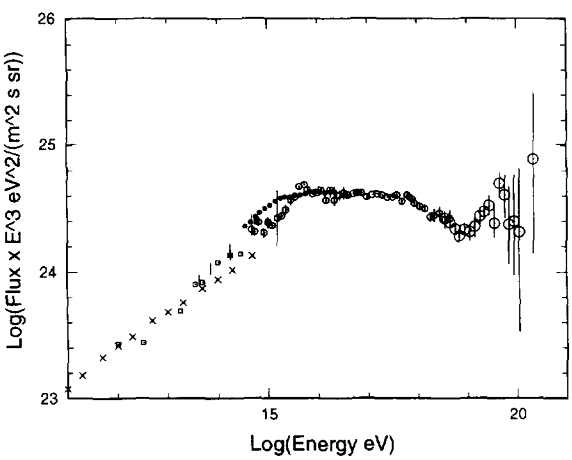


Figure 3. Differential energy spectrum of primary cosmic rays. Open circles:Akeno, closed circles:Tibet, crosses:Aoyama-Hirosaki, squares:Proton satellite, Bars:JACEE.

The Akeno energy spectrum between $10^{14.5}$ and 10^{18}eV is based on the number spectrum of total charged particles (shower size, N_e) in EAS. In the following we describe briefly how we have derived the energy spectum over five decades in energy and twenty decades in flux from the Akeno EAS experiments. The Akeno air shower array configuration for determination of shower size spectrum is called '1km^2 Array'(A1) [4] and is in the southeast corner of the AGASA. A1 consists of 156 scintillation detectors, each 1m^2 in area(6 out of which were 2.25m^2 till 1984), which are distributed over an area of about 1km^2 with detector spacing of 120m, and 30m in three regions of (90×90)m^2 area each where clusters of detectors were operated to observe the showers whose total number of particles around 10^6. In order to record the extensive air showers of N_e smaller than 10^6, a packed array consisting of 96 scintillation detectors of 0.25m^2 area was arranged in the north-east corner of A1. 25 scintillators of 3mm thickness were also arranged to calibrate the accurate number of electrons exceeding 0.5MeV. Since the lateral distributions of small showers are very flat, not only the packed array but the large array surrounding the packed array is indispensable to determine their core position, which is most important to evaluate the accurate flux of small showers.

Above 10^{18}eV, the particle density at a distance of 600m from the shower axis (S(600)) determined by the AGASA is used as an energy estimator, which is known to be a good parameter [10,11]. The lateral distribution of electrons and shower front structure at far from the core is investigated with many detectors of A1 by using showers hitting inside the Akeno Branch. The density at core distance r is expressed by the function as

$$\rho = N_e C_e R^{-\alpha}(1+R)^{-(\eta-\alpha)}(1+\frac{r}{2000})^{-0.5}, \quad (1)$$

where $R = r/R_M$, C_e is a normalization factor and R_M is Moliere unit (91.6m at Akeno) [12]. A fixed value of $\alpha = 1.2$ is used and η is expressed as

$$\eta = (3.80\pm0.05)+(0.10\pm0.05)\times log_{10}(N_e/10^9) \quad (2)$$

The effective collection area has been estimated

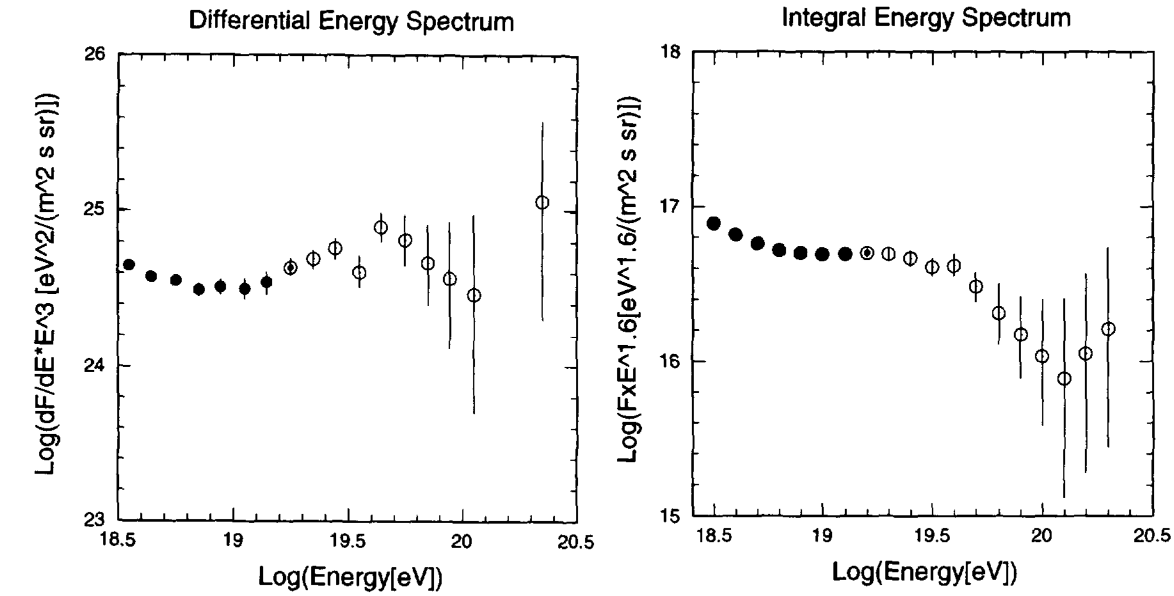


Figure 4. The differential and integral energy spectrum as determined by AGASA. New data (○) are normalized to our previous spectrum (·) at $10^{19.25}$eV.

through analysis of artificial showers which are simulated by using equation (1) with the observed fluctuation of density at each core distance.

The Akeno energy spectrum coincides very well with that determined by Tibet group (closed circles in figure 3 [6]) which may be the best one around knee region, since the shower sizes at Tibet altitude don't depend much on the shower development fluctuation and different primary composition. The small difference around 10^{15}eV between Akeno and Tibet spectrum may be due to the fact that some showers from heavy composition are attenuated considerably and can't be reached at Akeno level.

2.3. 'Ankle' Region

The differential and integral primary energy spectrum around the *ankle* is shown in figure 4 [13]. The bars represent statistical errors only and the error in the energy determination is about 40% around 10^{19}eV and 30% above $3 \times 10^{19.5}$eV.

The energy spectrum in the highest energy region from four different experiments are compiled in figure 5 with spectra from Haverah Park [14], Yakutsk [15] and Fly's Eye [16]. The spectra

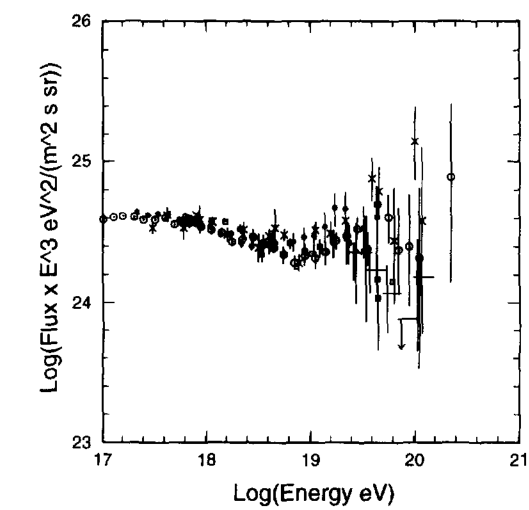


Figure 5. Folded energy spectra from the Haverah Park, Yakutsk, stereo Fly's Eye and AGASA experiments. All spectra are normalized to the stereo Fly's Eye result at around 10^{18}eV.

are normalized to the present AGASA result at around 10^{18}eV, since the Akeno spectrum coincides with the results at the lower energy region as described in the previous section. The multiplication factors for energies in the stereo Fly's Eye, the Yakutsk and the Haverah Park are 1.1, 0.9 and 1.0, respectively. It should be emphasized here that the agreement of the calorimetric method used by Fly's Eye and Yakutsk with the Monte Carlo based method used by Haverah Park and AGASA implies that the energy determination is rather good in these experiments.

The observed spectrum of figures 3 is best fitted to the simulated results under an assumption of diffuse sources distributed isotropically in the universe [17]. If this is true, we may not observe any anisotropy in the arrival direction distribution of these showers.

2.4. Arrival Direction

Recently Stanev et al. [18] have claimed that the arrival directions of events of energy $> 4 \times 10^{19}$eV from data sets based mainly on Haverah Park are correlated with the supergalactic plane. The supergalactic plane was originally defined by nearby bright galaxies in the northern hemisphere [19]. Later it has been shown that extragalactic radio sources also concentrate towards the same supergalactic plane and this concentration extends to at least z$\sim$0.02 [20].

The AGASA data are plotted in figure 6 for events with energy $> 4 \times 10^{19}$eV [21]. It is seen that arrival direction of significant fraction of EHECR are uniformly distributed over the observable sky, supporting the interpretation of energy spectrum at the highest energy end. However, it should be also remarked that two pairs of showers, each clustered within a 2.5°, are observed among the 20 events above 5×10^{19}eV, corresponding to a chance probability of 1.7%. If we consider 36 showers with energies above 4×10^{19}eV, another pair is observed at high supergalactic latitude with 2.9% chance probability. It should be noted that two pairs of them are within 2.0° of the supergalactic plane.

There is no experimental evidence for the primaries of pair events to be gamma-rays. Since decay length of a neutron is about 1Mpc at 10^{20}eV, neutrons after production and escape from the large magnetic field environment around a source must travel most of their way through intergalactic space as protons.

If the primary particles are protons, significant constraints are imposed on the scale, the strength and the direction of the magnetic field configuration and its turbulence in the interstellar and intergalactic space to explain pair events with angular separation of only a few degrees.

In figure 7 are shown the distributions in galactic and supergalactic latitudes for AGASA and other experiments reported in [18]. Solid curves are the expected values from uniform arrival direction distribution in the whole sky. There is a concentration of events in the 0° $\sim$ 10° bin of about 1.6σ.

2.5. Fly's Eye experiment and composition

The University of Utah group performed the experiment by observing nitrogen fluorescence excited by electrons of EAS [22]. Showers appear as light streaks across the sky. They covered the whole sky with 67 mirrors of 1.6m diameter each. A light streak was observed with 873 photomultiplier tubes. The shower energy is measured by detecting the longitudinal development profile of the extensive air shower and hence determined calorimetrically. A disadvantage of this experiment is the limitation on observation time to only about several % of the total time.

A major advantage of the optical method is its capability of measuring the depth for the maximum shower development (X_{max}). Since X_{max} correlates well with the depth of first interaction (mean free path) of primary cosmic rays, the distribution of X_{max} depends on the chemical composition of the primary flux. For example, the average X_{max} differs approximately by 80 g/cm^2 between showers initiated by iron and proton primaries [23].

Figure 8 shows the comparison of the experimental results from Fly's Eye with the expected energy dependence of X_{max} for proton and iron primaries obtained from simulations [24]. Their interpretation of this result is that the proportion of protons increases with increasing energy and is about 90% at 10^{19}eV.

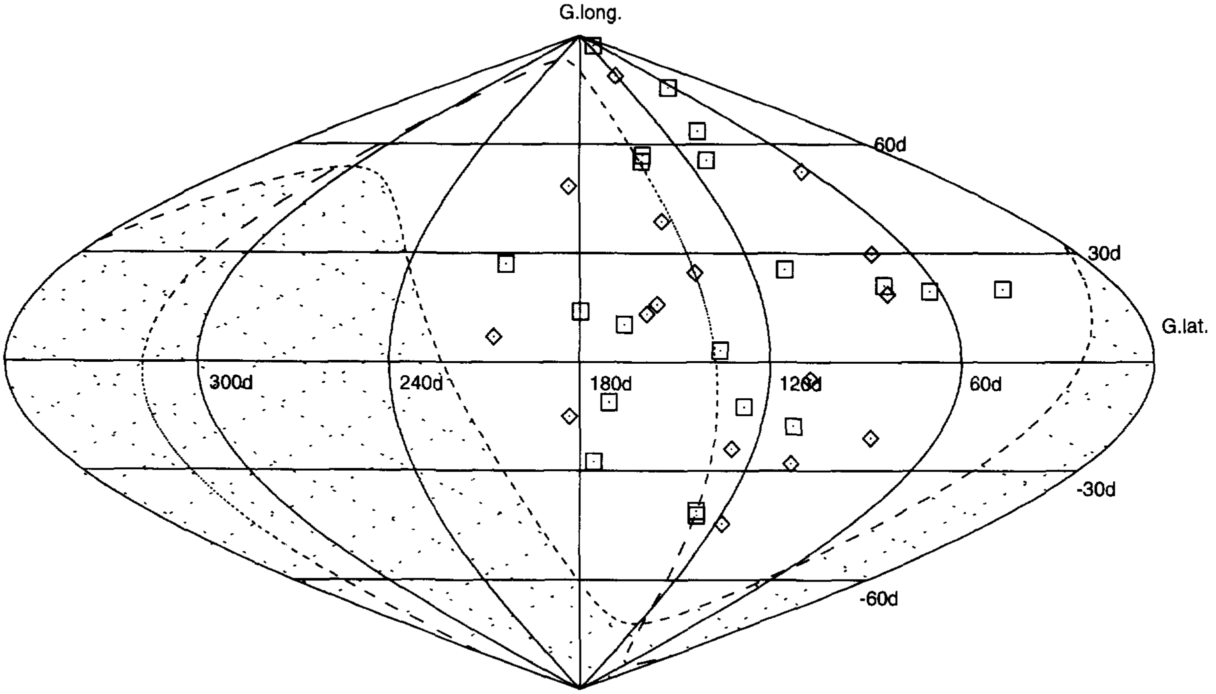


Figure 6. Arrival direction distribution of 36 cosmic rays above 4×10^{19}eV in galactic coordinates. Open squares represent events above 5×10^{19}eV (20 events) and open diamonds between 4×10^{19} and 5×10^{19}eV(16 events). The dashed curve shows the supergalactic plane and sky not observed by AGASA due to a zenith angle cut at 45° is shown as cross-hatched area.

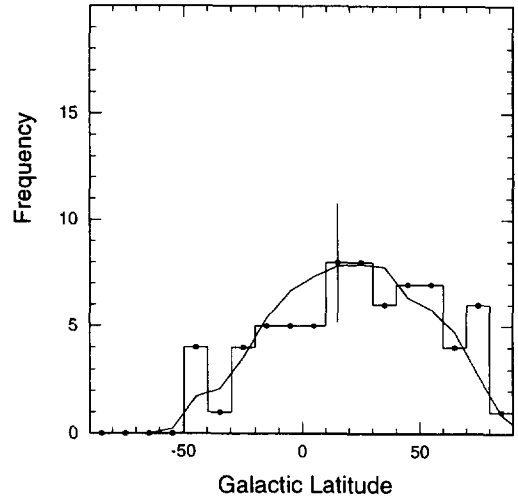
Since total number of muons from heavy primaries is larger than that from light ones for equal primary energies, the ratio of the muon component to the electron component may become smaller in this energy range than the extrapolated value from the lower energy region, if the above Utah group's finding is due to a change in the primary composition. In figure 9, the AGASA result [28] on muon density at 600m from the core ($\rho_\mu(600)$) and S(600) relation is plotted, along with the expected relation from Fly's Eye two composition model by a Monte Carlo simulation based on the MOCCA program [25–27]. The change of the composition above $10^{17.5}$eV has not been detected beyond the experimental uncertainties and assumptions used in the simulation. Further observations are required for confirmation of Fly's Eye results.

2.6. The highest energy events

There are two events whose energies exceed considerably the GZK cut-off energy. One is an AGASA event [29] and the other is a Fly's Eye event observed by the optical method [30]. Both events have been studied carefully and are believed to be really beyond the GZK cutoff.

As shown in figure 1, their sources can't be very far and must be within a few tens of Mpc. There are no candidate astronomical objects within a few tens of Mpc in the direction of the highest energy events which may be able to accelerate particles to more than 10^{20}eV and there is an apparent gap in the existing data between the highest energy events and other events.

These observations have led to suggestions that



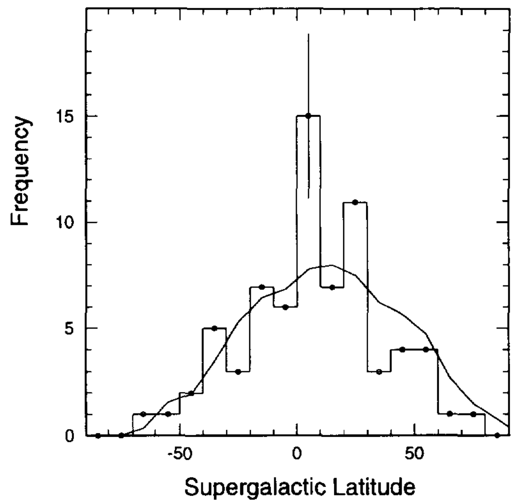


Figure 7. Galactic (left) and supergalactic (right) latitude distributions of arrival directions of cosmic rays of energies above 4×10^{19}eV of AGASA (36 events), Haverah Park (27 events), Volcano Ranch(5 events) and Yakutsk(3 events).

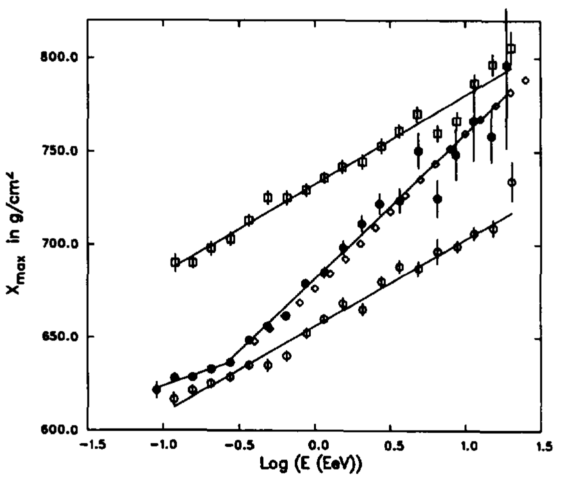


Figure 8. X_{max} distribution by Fly's Eye experiment(dots). Energy dependence from proton and iron primaries obtained by simulations are plotted by open squares and open circles respectively.

particles may be directly produced by decay from objects produced in phenomenon occurring on a higher energy scale. For example, topological defects (TD's) left over from the phase transitions in the early universe, caused by the spontaneous breaking of symmetries, have been proposed as a candidate for production of extremely high energy cosmic rays [31]. Such TD's are magnetic monopoles, cosmic strings, domain walls, superconducting strings etc. The remarkable result from this scenario is that bulk of cosmic rays above 10^{20}eV may be gamma-rays rather than protons. Also, there is expected to be a gap around 10^{20}eV and the energy spectrum is expected to extend up to the GUT scale $\sim 10^{25}$eV with a hard exponent such as 1.35 [32], which is based on the exponent of hadronization in QCD.

3. FUTURE PROJECTS

In order to increase the statistics of EHECR's significantly, three projects are now under construction or preparation.

3.1. The HiRes Detector

The University of Utah group is promoting the High Resolution Fly's Eye Detector (HiRes)

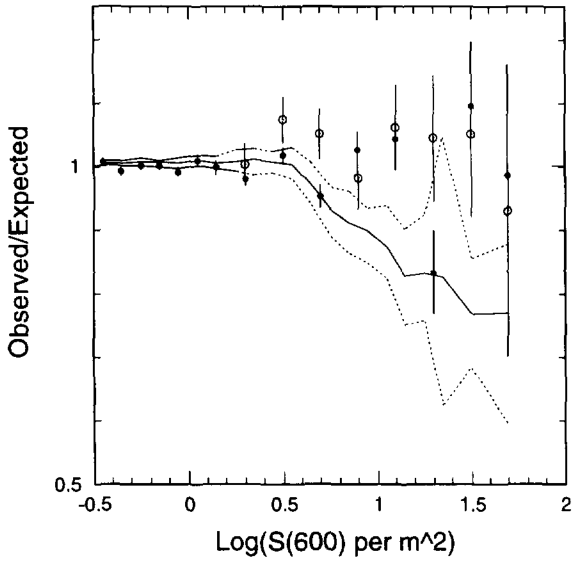


Figure 9. $\rho_\mu(600)$'s divided by expected values are plotted as a function of S(600). The expected densities are extrapolations from the average relation determined below $10^{17.5}$eV. An expectation from two composition model proposed by the Fly's Eye group is shown by dotted lines (68% C.L.) and a solid line (the average) respectively.

which will have greatly improve energy resolution and composition measuring capabilities. [33]. The Phase I of HiRes is now under construction, which consists of two stations, each station has 240 degree azimuthal coverage and particle elevation coverage of 27 degrees above the horizon. Each station consists of 54 mirrors. In the focal plane of each mirror, 256 hexagonal phototubes view a 16×13.5° section of the sky. The reconstructible stereo aperture for the two partial stations is expected to be about 3400km^{2}sr at 10EeV. The full scale HiRes is designed to have a 10,000km^{2}sr aperture, however, has not yet been funded.

3.2. The Telescope Array Project

In Japan the Telescope Array Project [34] is under preparation. In this project more than 100 telescopes, each 3m in diameter, are planned to be deployed with 50m separation as demonstrated in Fig.10. Each telescope consists of 19 hexagonal segment mirrors. On the focal plane of each telescope, an imaging camera with multianode photomultipliers is to be installed. After several years of observations, the distance scale for cosmic ray sources may be clearly distinguished. Another purpose of the Telescope Array Project is to observe high energy gamma-rays from point sources in the sub-TeV energy region. Gamma rays will be distinguished from the large background due to cosmic rays such as protons from the imaging patterns observed with many telescopes.

3.3. The Pierre Auger Project

The Pierre Auger Project [35] is an international collaboration work under preparation. 1657 detectors will be deployed in an area covering about 3000km^2 with about 1.5km separation. The arrays will be set up both in the southern hemisphere and the northern hemisphere to cover the whole sky. Argentina has already been decided to be the site in the southern hemisphere. The site in the northern hemisphere will be decided in this September. Each surface detector is a water tank of 10m^2 area and 1.2m depth. Power is supplied by a solar panel and GPS is used for timing at every station. Communication between the center and detectors will be made by a cellular phone system dedicated for this purpose. At the center of the array, 78 mirrors of 4m diameter will be installed as an air fluorescence eye. 256 photomultiplier tubes will be used, each photomultiplier covering an area of 1° radius in the sky.

4. CONCLUSION

It is most likely that EHECR's are from diffuse sources distributed isotropically in the universe. However, some fraction of cosmic rays beyond 40EeV seem to come nearby sources composing double or triplet events within a limited space angle.

If the HiRes Detector, Telescope Array Project and Auger Project are constructed, the observed rate for 10^{19}eV showers is expected to be several thousands/year and several tens/year for 10^{20}eV. The shape of the primary energy spec-

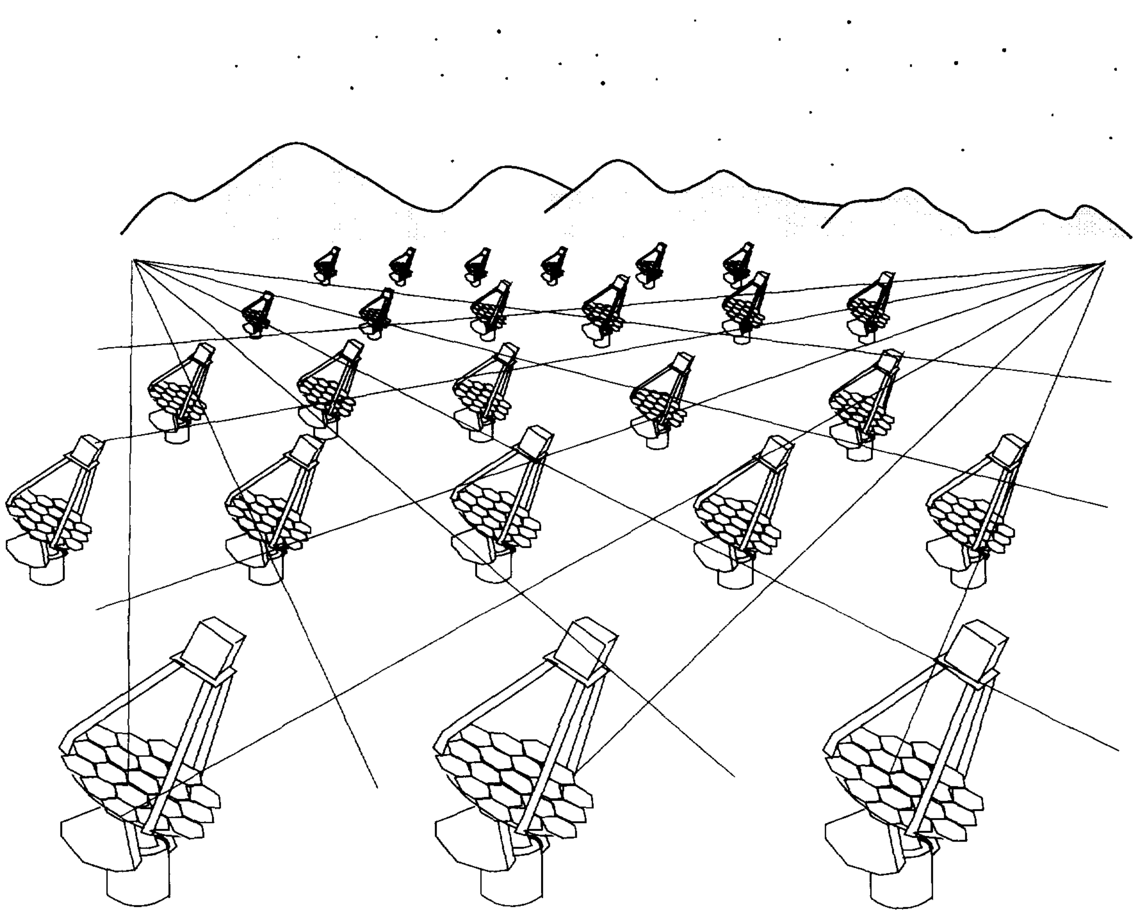


Figure 10. Artistic view of the Telescope Array Project

trum around the GZK cutoff would be clearly determined and hence the average distances to the sources may be known. The correlation with the the supergalactic structure may be confirmed and some astrophysical objects of extremely high energy cosmic rays may be identified. There is a possibility of observing several showers exceeding the cutoff energy, whose origin might be beyond our present speculations.

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