Historical Review on Ultrahigh-energy Cosmic Ray Experiments

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The experiments on search for the end of the cosmic ray energy spectrum, with the shower array technique and the fluorescence technique, are summarized. Other techniques which have not been operated successfully are briefly reviewed. The energies of $> 10^{20}$ eV candidate events reported by the INS-LAS array and SUGAR are reevaluated. Three of them may be above 10^{20} eV and the arrival direction distribution of eighteen 10^{20} eV candidates so far observed in the world is shown.

KEYWORDS: cosmic ray history, ultrahigh-energy cosmic ray

§1. Introduction

There is a review on the history of the cosmic ray studies by J.Linsley,$^{1)}$ in which the early experiments to search for its composition and for end of its energy spectrum is described in detail, starting with its discovery by V. Hess in 1912. The early air fluorescence work at Cornell and in Japan is described by G.Tanahashi$^{2)}$ in the same proceedings. Recently M.Nagano and A.A.Watson$^{3)}$ reviewed the observations and implications of the ultrahigh-energy cosmic rays and the related references are found there. In this review, the experiments on search for the end of the cosmic ray energy spectrum is described after the discovery of 10^{18} eV cosmic rays around 1957. Above this energy we define here as "ultrahigh-energy".

In Fig. 1 are shown various experiments on ultrahigh-energy cosmic rays, where main periods of experiments are shown.

First the history of the particle array technique is reviewed and then the fluorescence technique. Other techniques which have not been operated successfully is described briefly.

§2. Particle array technique

2.1 The MIT-Agassiz array

During the period 1947-55, the MIT group$^{4)}$ developed techniques of "density sampling" and "fast timing", in which the pattern of densitities observed with an array of scintillation counters is used to locate the core of the extensive air shower (EAS) and its arrival direction is determined from the differences among the arrival times of shower particles at various counters. Between 1954 and 1957 an array of 15 counters, each 1.0 m^2 area, was operated at the Havard Agassiz Station$^{5)}$ and the energy spectrum up to 10^{18} eV was derived. A liquid scintillator of about 25 gallons (about 1000 litres) of toluen was used as a counter, however, one of the counter was burst into flames due to lightning. Accordingly a large scale plastic scintillator was developed and the liquid scintillators were replaced by the plastic ones in 1956. The largest shower recorded in this experiment is about a few times 10^{18} eV as shown in Fig. 2 .$^{4)}$ In this experiment the feasibility of the fast timing method for determining arrival directions and not only the analog device (computor) but also the digital computation for determining the core locations were demonstrated. These methods are the basis of particle array experiments afterwards.

2.2 The Volcano Ranch array

After the Agassiz experiment, J.Linsley, L.Scarsi and B.Rossi$^{6)}$ constructed a large array at Volcano Ranch in New Mexico and extended the primary energy spectrum to above 10^{19} eV. The detectors were nineteen 3.3-m^2 plastic scintillation counters on the surface and those shielded by 10 cm of lead. Then the signals were displayed on oscilloscope for measurement of pulse amplitude and the relative arrival time of muons and all charged particles separately. With this array J.Linsley discovered the first event estimated to be 10^{20} eV in 1962 during three years of full-scale operation.$^{7)}$ It should be noted that this event was before the discovery of the 2.7K background radiation$^{8)}$ in 1965 and prediction of a cutoff (GZK-cutoff) in the primary cosmic ray energy spectrum by K.Greisen,$^{9)}$ and Z.T.Zatsepin and V.A.Kuzmin$^{10)}$ in 1966.

2.3 The Haverah Park array

Soon after the prediction of this GZK-cutoff, two large arrays, at Haverah Park in UK and at Narribri in Australia started their operations from 1967. In Fig. 1 are shown the years of steady operation in full scale of each experiments. Tokyo INS group constructed a sub-large array in 1968.

Main detectors at Haverah Park were water Čerenkov detectors laid out over about 12 km^2.$^{11)}$ Each tank was 2.25 m$^2\times$1.2m and 15 tanks (in total 33.75 m^2) were deployed in each station. Communication of a trigger coincidence was made to the outer stations via a 7.0-GHz microwave link. This array was operated in stable for about 20 years without any deterioration of water quality. 4 events whose estimated energy above 10^{20} eV

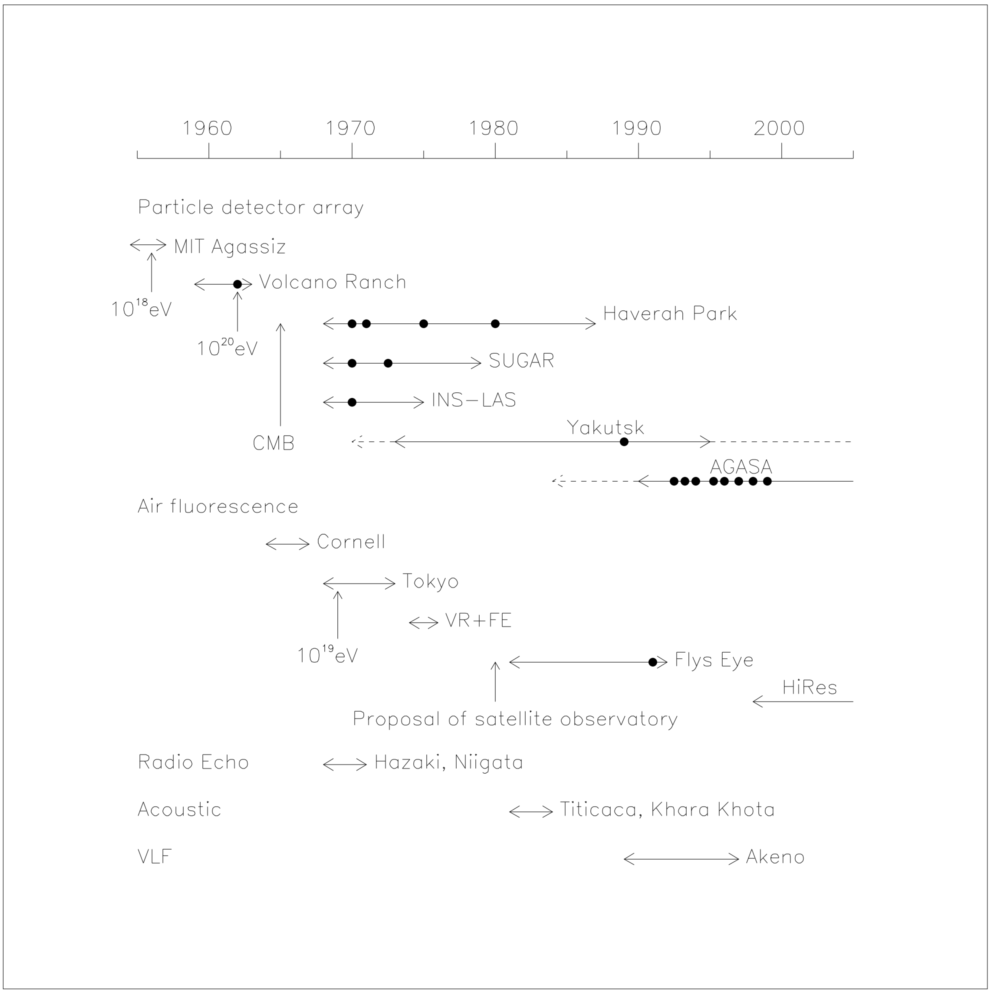

Fig. 1. Chronology of ultrahigh-energy cosmic ray experiments. The years of the first observation of 10^{18} eV event and 10^{20} eV event are shown by arrows. The first observation of clear fluorescent light from EAS is indicated by an arrow with 10^{19} eV. Closed circles show the years when 10^{20} eV candidates were observed. Years of SUGAR events are not reported and the positons of their marks are not accurate.

are reported.11)

In the ground array technique, we should remark that fluctuation of the density of shower particles far from the core is quite small irrespective of hadronic interaction model or chemical composition of the primary particle and hence the density far from the core is a good estimator of primary energy. This insight was first pointed out by A.M.Hillas12) in 1970 and have been supported by many simulation studies afterwards.13–15) Without this idea, the energy estimation of primary particle has never been successful in the groud array experiments, where detectors are deployed in wide separation. The Haverah Park group first used this parameter and estimated the primary energy reliably.

2.4 SUGAR

The Sydney University Giant Air-Shower Recorder (SUGAR) started its operation at Narribri in 1968. 56 stations, each of which consisted of a pair of 6-m^2 scintillators buried 1.7 m below ground.16) Though the area covered was over 60 km^2, the spacing between the stations, typically 1.61 km, was too great to determine a core location, energy, arrival directions of EAS with enough number of hit stations. Furthermore, afterpulsing in the 7-in. photomultipliers was a serious problem throughout the lifetime of the experiment, as logarithmic time to height converters were used. Nine events whose energies were estimated to be nearly above 10^{20} eV were reported.17) Zenith angles of two events were about 70° and their core locations were outside the boundary of the array. In three other events, hit stations were only three and detector response of one of hit stations was saturated. These events may not be considered to be definitive candidates of 10^{20} eV. In the following we evaluate the primary energies of four other events by using the muon lateral distribution18) determined by Akeno Giant Air Shower Array (AGASA).27)

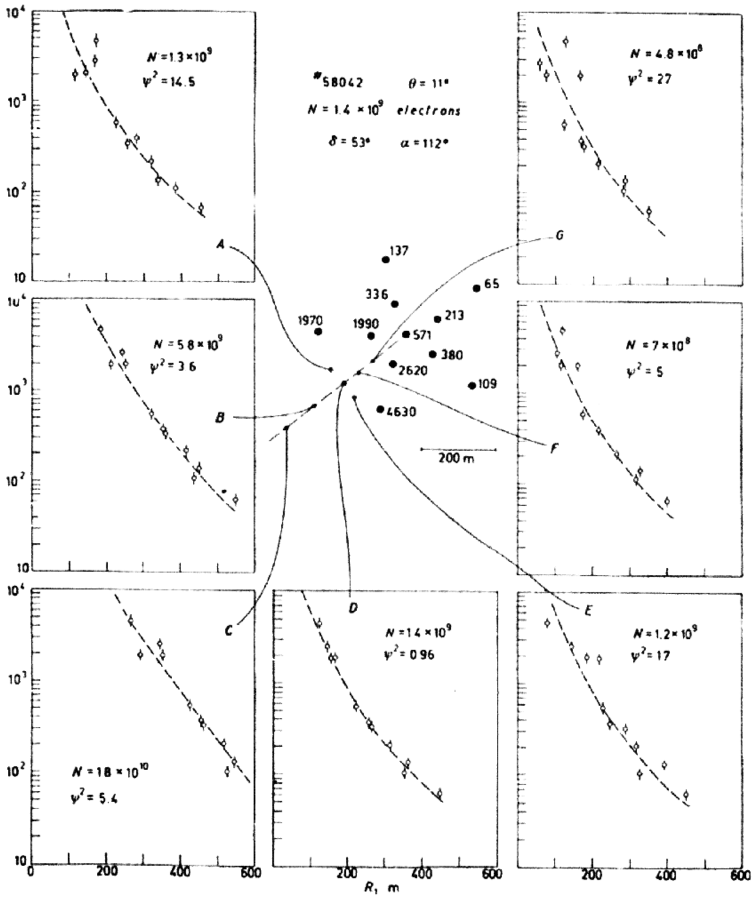

Fig. 2. Analysis method of the particle densities measured in the largest shower recorded in the MIT-Agassiz experiment.[4)] Core location D gave the best fit to a smooth curve.

In Fig. 3 are shown the lateral distributions of muons of four events. Experimental points are densities per 6-m^2 and vertical lines indicate operational and non-triggered stations, whose threshold densities correspond to three vertical muons in the tank. This is because a master pulse was produced at each station if the two tanks were triggered above vertical muons in the tank. The dashed lines are the lateral distribution determined by SUGAR and described in Brownlee et al.[20)] Estimation of primary energy in EeV using Hillas model E [21)] is indicated. The lateral distributions converted to the corresponding depth and threshold muon energy of each event from the AGASA empirical lateral distribution [18)] are shown by solid lines. It is clear that the AGASA one is better fitted to the experimental points than the SUGAR one, especially to non-triggered stations. Though the energies of SU14427 and SU6179 are in good agreement with the estimation from the AGASA lateral distribution of similar energies, SU14596 and SU12420 are better fitted to those of 32 EeV and 63 EeV, whose functions are drawn by dotted lines. At least two events (SU14427 and SU6179) may be 10^{20} eV candidates, if the extrapolation of AGASA muon lateral distribution to the depth of individual SUGAR event is valid.

2.5 *The INS-LAS array*

At Tokyo K.Suga et al. constructed an INS-LAS array in 1968, which was large compared with the previous INS array, however, was relatively small compared with those at Haverah Park and at Narribri. The primary purpose of this array was to use the decoherence method or the density spectra at different separations of detectors to estimate the primary energy spectrum. They reported the detection of a $4{\times}10^{21}$ eV cosmic ray in 1970,[22)] whose energy was estimated from the total number of charged particles by fitting the lateral distribution by J.Linsley.[23)] Here we review it how much energy was that with using the AGASA lateral distribution of charged particles and muons.[18)] In case of charged particles, the difference of Mòliele Unit between INS and Akeno must be taken into account. Hence the energy conversion equation E=$3.27{\times}10^{17}{\times}$S(600) is used, where E is primary energy in eV and S(600) is a partile density per 1 m^2 at 600 m from the core. The left figure of Fig. 4

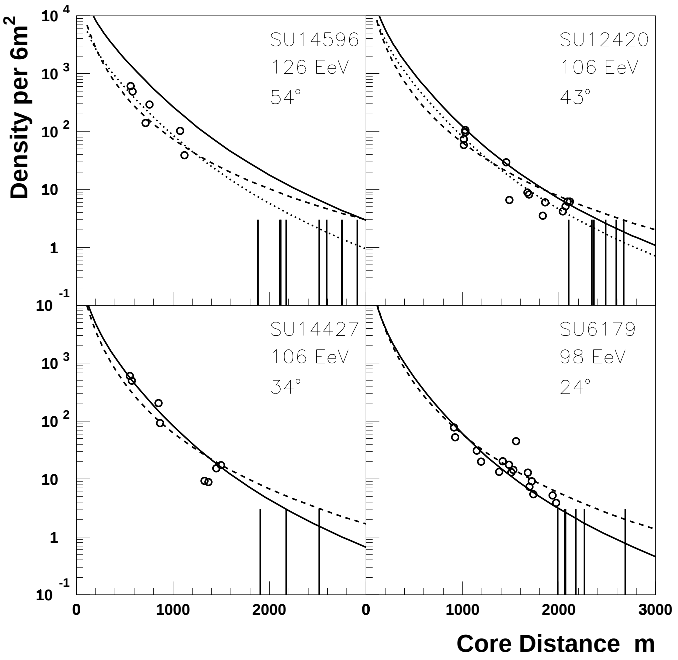

Fig. 3. Energy estimation of SUGAR events. Serial number, estimated energy and zenith angle given in the catalog[17)] are listed in each graph. Densities per 6 m^2 are plotted by open circles and operating and non-triggered stations are shown by vertical lines. Dashed lines are lateral distibution of muons used by the SUGAR analysis. Solid lines are extrapolated one to the corresponding atmospheric depths from the one determined by AGASA with primary energies given in the catalog. Dotted lines of SU14596 and SU12420 are better fitted to the AGASA lateral distribution than the SUGAR one and their energies are 32 EeV and 63 EeV, respectively.

shows the reanalysis by fitting the charged particles on surface and muons underground. The right one is the detailed fitting for densities of twenty two 1-m^2 scintillation detectors near the core, whose data was shown in a report.[24)] In case of the original core position by the authors, the energy is about 10^{21} eV, but the fitting is not good at large distances. If we move the core nearer to the INS array (closed triangles), the data can not be fitted again far from the core. The data may be best fitted to $10^{20.4}$ eV (closed squares) in wide range of core distances. The muon densities can be also fitted within experimental uncertainties. Though the original energy assignment of 4×10^{21} eV is too large, however, it may be about 2.5×10^{20} eV and is still one of the highest energy events reported so far.

2.6 The Yakutsk array

The Yakutsk array in Siberia is the most complex of the giant arrays. This array bagan taking data in 1970 and was developed to cover an area of 18 km^2 in 1974.[25)] Not only surface detectors, many underground detectors are deployed. A particularly important feature of this installation has been the presence of 35 photomultiplier systems to measure the air Čerenkov radiation associated with the showers. These are useful to provide a calorimetric approach to calibration of the primary energy experimentaly, since the energy estimation of other particle array experiments are based only on simulation studies. One event above 10^{20} eV whose zenith angle is 58.9° is reported.[25)] Though the Yakutsk group estimated the primary energy carefuly, the observed shower particles are mostly muons, and the energy determination depends critically on the primary mass and hadronic interaction model assumed.

In 1995 the Yakutsk array was rearranged to 10 km^2, so that detailed studies of shower structure could be made around 10^{19} eV, where they have reported a change of shower characteristics.[26)] The recent results from the Yakutsk experiment may be described by A.A. Ivanov in this proceedings.

2.7 AGASA

AGASA is the largest array constructed so far, covering an area of 100 km^2.[27)] The communication network through a string consisting of two optical fibers has been employed and hence the accumulation of data is quite in stable with duty factor above 95% since its beginning of operation in 1990. The number of events reported above 10^{19} eV, 4×10^{19} eV and 10^{20} eV with zenith angles

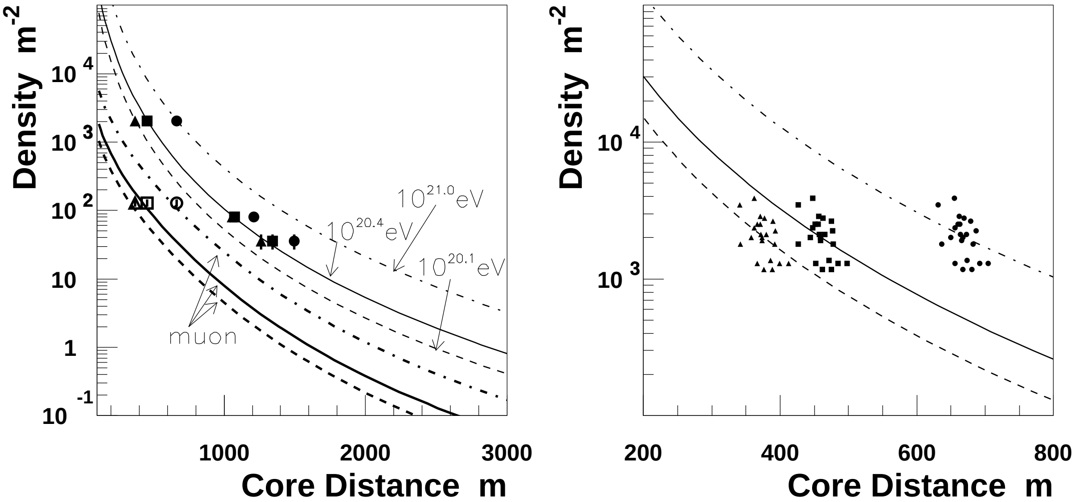

Fig. 4. Energy estimation of the largest event of INS-LAS array with the lateral distributions of charged particles and muons determined by AGASA. Right figure shows the distribution of densities of 22 scintillation detectors of 1-m^2 area each cited from the figure in K.Suga.[24] Closed marks are densities observed by scintillation counters on the surface for different core locations and open ones are those underground. Dot-dashed, solid and dashed lines correspond to those of 10^{21} eV, $10^{20.4}$ eV and $10^{20.1}$ eV respectively. The primary energy is clearly higher than 10^{20} eV and may be 2.5×10^{20} eV.

less than 45° are 716, 51 and 8, respectively.[28,29] The analysis is still under development and the number of events may be increased by 50% if we include the events of zenith angles up to 60°. The new results may be described in this proceedings by N.Sakaki and M.Takeda.

2.8 Pierre Auger Observatoy

The construction of an engineering array of the Pierre Auger project started in 1999 in Argentina and the present status may be described by M.Boratav in this proceedings.

§3. Fluorescence technique

3.1 The Cornell experiment

The possibility of using the earth's atmosphere as a vast scintillator was pointed out at the Norikura Symposium in 1958.[2] The pioneering discussions have been made by K.Suga[30] and A.E.Chudakov[31] at the 5th Interamerican Seminar at La Paz, Bolivia. Based on the experimental measurement of fluorescence efficiency in air produced by deuteron beam,[32] the first station was constructed on the hill of Mt.Pleasant near Ithaca in 1964 by K.Greisen and his group.[33] With two additional stations forming a triangle with distances of 11, 16 and 12 km, the experiment was continued till 1967. In 1965, K.Greisen proposed a new system to devide the celestial sphere into about 500 mosaic segments and to record the light intensity and its arrival time of each segment. This imaging system with 25 sided observatory shown in Fig. 5 was constructed in 1966.[34] However, due to the severe climate of Ithaca in winter and the low statistical chance to have very high energy showers prevented them to catch clear fluorescent light from EAS. This idea of the system may be the basis of the fluorescence detectors which have been developed afterwards.

3.2 The INS-Tokyo experiment

After returning from the Cornell experiment, G.Tanahashi started another experiment in 1968 at Mt. Dodaira near Tokyo with the Fresnel lens of 1.6m diameter and 27 photomultiplier tubes (PMTs) at the focal plane.[2] Within 6,000 events recorded during 90 hours, his group luckily succeeded in detecting the first fluorescence light from EAS of energy above 5×10^{18}eV.[49] This event was clearly distinguished from other Čerenkov light events, since the angular velocity of signals on each PMT was measured to be about 0.08 rad/0.45 μsec and the light intensities from each PMT to be almost constant, which indicated that the shower distance of 1.7 km if the shower fell at right angle with the line of sight and the shower was nearly at its maximum development. Encouraged with this event his group constructed another two types of telescopes, however, the further development was not successful, because the plastic lens used was mixed one with UV stopper.

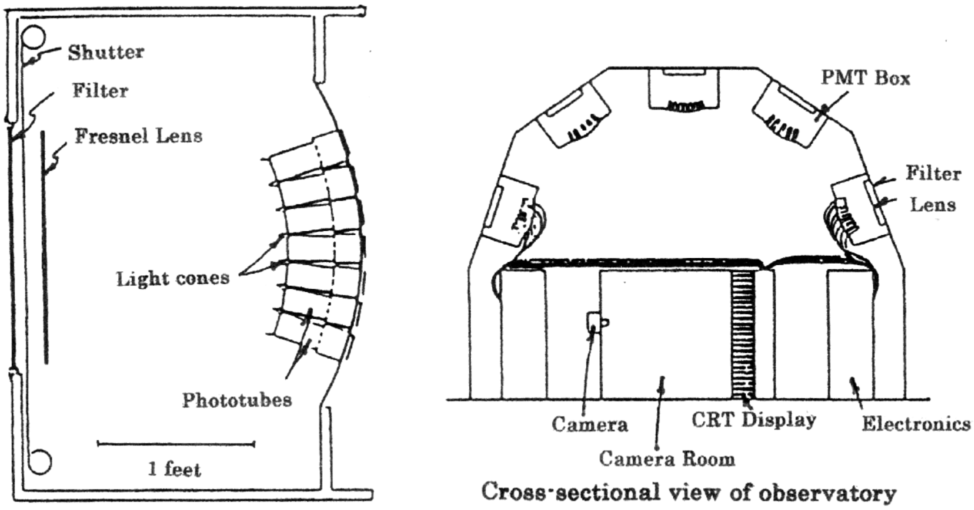

Fig. 5. Cornell imaging system with 25 sided fresnel lens and 500 mosaic segments (photomultiplier tubes) (from G.Tanahashi[2]).

3.3 Fly's Eye detector

In 1974, the proposal of Fly's Eye was anounced by the Keuffel's group at the University of Utah. In 1976 unambiguous detection of fluorescent emission from showers, in coincidence with a ground array at Volcano Ranch, was established.[36]

This success led to the construction of the Fly's Eye detector and the operation started in 1981[37] at Dugway near Salt Lake City. There were two detectors, Fly's Eye I (FE I) and Fly's Eye II (FE II), separated by a distance of 3.4 km. The FE I consisted of 67 mirrors of 1.6-m diameter and in total 880 phtomultipliers were used to cover the whole sky. The observation continued for more than 10 years. However, a lot of pioneering work, such as the optical calibration system,[38] the atmospheric monitoring methods,[39] were required to derive the fruitful result of the energy spectrum of primary cosmic ray, measurement of the depth of the maximum shower development and so on. This may be why the highest-energy event so far observed by any detector was detected in 1991, but the details were published in 1995.[40] The Fly's Eye experiment showed the importance of the stereoscopic observation of the event and established the basis of both experimental and analysis method.

3.4 HiRes detector

A successor to the Fly's Eye instrument, known as HiRes, started to take data at Dugway. This is expected to have a time-averaged aperture of 340 km^{2}sr at 10^{19} eV and 1000 km^{2}sr at 10^{20} eV. The recent result from the HiRes may be described by L.Wiencke in this proceedings.

3.5 The next generation detector

The next generation fluorescence detector, the Telescope Array Project is under preparation in Japan and the present status may be described by M.Sasaki, K.Martens and T.Yamamoto in this proceedings.

The possibility of detection of fluorescent light from the satellite was discussed by J.Linsley[41] before the Fly's Eye was successfully operated. His idea is now in realistic stage as EUSO experiment, which may be described by L.Scarsi in this proceedings.

It should be noted that the measurement of fluorescence efficiency of electrons (above 1MeV) in dry air was made by F.Kakimoto et al.[42] in three wave length bands, 337.1nm, 357.7nm and 391.4nm, and in wide band 300$\sim$400 nm. In most fluorescence experiments, efficiencies are used from the early measurements by charged particles stopping in air summarized by A.N.Bunner.[32] The relative fluorescence efficiencies among 337.1nm, 357.7nm and 391.4nm are quite different in measurements between 1.4MeV electron and charged particles stopping in air. It is necessary to measure them by fast electrons in other wave lengths in order to estimate the fluorescence efficiency for the different type of filters used in each experiment.

§4. Other techniques

It is quite important to explore any new detection method in any field in any time. In the following some trials to search for the end of the cosmic ray spectrum is described, which were discussed and explored in Japan led by K.Suga.

4.1 LF-MF radio signals

It is well known that the EAS are accompanied by radio-frequency signals and studied in detail in

1967∼73.[43] These radio signals are mainly due to (i) Čerenkov emission from excess electrons in the shower and (ii) dipole current and dipole moment from the separation of positive and negative electrons of the shower in the Earth's magnetic field. In order to be observed coherently, the wave lengths must be longer than the thickness of the shower front (1∼3 m) and hence the observation was limitted to near the core of EAS. K.Suga proposed a possible detection of radio signals at frequencies less than 1MHz far from the core associated with large EAS and started the experiment at Akeno in coincidence with the AGASA since 1989. K.Kadota and F.Kakimoto continued this experiment triggered by AGASA till 1997.[44] Three 10-m vertical antennas were used in about 1 km separation. Outputs of the antenna were stored in a wave form recorder after passing high-pass and muti-band elimination filters and amplifiers. Emission mechanism is concluded to be due to the acceleration of ionized electrons in the atmospheric electric field (10 V/m ∼ 300 V/m near the ground).[45] Not only the proportion of events associated with radio signal is too small, but also fluctuation of signal amplitude is too large to apply this method for the detection of UHECR.

4.2 Acoustic signal

Detection of acoustic signal produced in water by high energy hadrons in air shower core has been proposed by T.Bowen.[46] This is due to the adiabatic expansion produced by instantaneous heat deposition. Since a large fraction of hadronic components remains in the shower core at high altitude, K.Suga proposed the detection of UHECR at Lakes in Bolivia and his group measured the water temperature throuout a year and acoustic background noise and tested various types of hydrophones at Lake Titicaca (3812 m.a.s.l.) and the Lake Khara Kkota (4300 m.a.s.l.) from 1981 to 1984.[47] In order to detect 10^{20} eV events, more than 100 hydrophones with quite-high sensitivity are required to increase S/N ratio.

4.3 Radio echo

This idea is based on the reception of the echo of a pulsed radio wave from the ionized colomn of air molecules produced by an air shower and its possibility was proposed by K.Suga.[30] While the collision mean free time of electrons is very short, about 10^{-9} s, the mean life for recombination of the positive and negative ions is several minutes. A preliminary experiment was made in Hazaki and Niigata in Japan around 1970 by searching for any reflected signal from Loran pulsed radio wave (1850 kHz) .[48,49] In order to depress the random noise signal, about 10^4 echo pulses expected from column of ions for several minutes were integrated. It was found that the time variation of 6-9 seconds and 1-5 minites from a reflection of radio waves by sea waves remained as noise. Though the former was easily depressed with filters, the latter limitted the detection of the signal from the air shower on the sea. It was required to try the experiment at the Arctic. An important conclusion of this experiment is that the height of *tsunami*, tidal wave, originated from earth quake may be estimated about 100 km far before arriving the sea shore.

§5. Conclusion

After the discovery of 10^{20} eV cosmic ray in 1962, 18 candidates of cosmic rays above 10^{20} eV are observed, including 3 candidates from INS-LAS and SUGAR reevaluated in this report. In Table I are listed four additional 10^{20} eV events which should be added to the list in M.Nagano and A.A.Watson .[3]

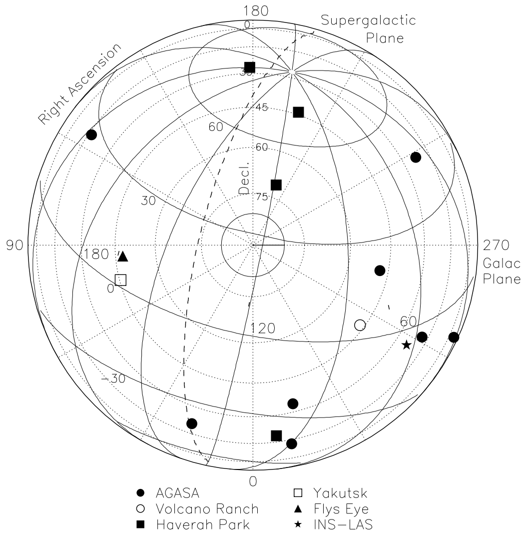

Fig. 6. Arrival directions of 10^{20} eV events on the equi-exposure map of AGASA. The center is the north pole and the declinations of 75°, 60°, 45°, 30°, 15° and 0° are drawn by dotted concentric circles. Galactic latitudes and longitudes are drawn by solid curves in each 30°. The supergalactic plane is shown by a dashed curve. SUGAR events in the Table I are outside this map and are not plotted. They are within 10° from the galactic plane.

These are plotted on the equi-exposure map of AGASA in Fig. 6. Including two events from SUGAR in Table 1, eight events out of 18 are within 10° from the galactic plane. It should be noted that only 20% are expected if they are from isotropic distribution. Another important result so far is the possible clustering of ultrahigh-energy cosmic rays as AGASA experiments shows. We expect more events from the next generation experiments in the northern and southern hemispheres with much higher angular resolustion than AGASA.

Acknowledgement

The author gratefully acknoweledges the late Prof. K.Suga for his guiding me to the ultrahigh-energy cosmic ray experiment. He is also grateful to the members of AGASA experiment for their cooperation.

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Table I. List of candidate events above 10^{20}eV which are not included in the list of Nagano and Watson.[3)] Energies of the INS-LAS and SUGAR events are estimated in the present analysis. The AGASA event is from Hayashida et al.[29)] Observation date of SUGAR experiment is not reported.

Experiment	Date	Energy 10^{20}eV	Z.angle degrees	RA	Decl.	l	b	Ref.no.
				degrees		degrees		
INS-LAS	10.11.70	2.5±0.5	20	303	24	63.9	-5.7	
SUGAR		1.0	24	122	-31	249	0.9	6179
SUGAR		1.0	34	130	-26	249	9.7	14427
AGASA	22.09.99	1.0	35.6	345.8	33.9	98.5	-23.8	05343-957

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