Extremely High Energy Cosmic Rays—Experiments, Theories and Future Direction—
J. Phys. Soc. Jpn. Vol. **70** (2001) Suppl. B pp. 204–205

Future Directions of Extremely High Energy Cosmic Ray Experiments

Masaki Fukushima*

Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277–8582, Japan

A brief summary is made for the planned large scale air shower experiments for the Extremely High Energy Cosmic Rays (EHECR's) presented in the workshop.

§1. Review of the History

Indications of cosmic ray air showers with energy 10^{20}eV or higher have been accumulated gradually since 1960's.[1–4] Its existence has recently been established by the AGASA air shower array.[5,6] The AGASA has an acceptance of 180 km^2 str, which is 5 – 10 times larger than previously operated ground arrays. It recorded 8 events with energies exceeding 10^{20}eV in 9 years of operation. Arrival directions of these events have no clear correlation with the galactic matter distribution.

It has been pointed out that the cosmic microwave background (CMB) filling the universe impedes the propagation of extremely high energy protons by forming the nucleon resonance with high cross section. This effect predicted by Greisen, Zatsepin and Kuzmin (GZK) results in a sharp cutoff in the energy spectrum of extra-galactic cosmic rays around 10^{20}eV.[7,8] Conversely, if we observe cosmic rays with energy higher than 10^{20}eV, most of them must originate within $\approx$50 Mpc of our galaxy.

The energy spectrum observed by AGASA continues toward high energy without showing the indication of the GZK cutoff. The large and strong astronomical objects such as the active galactic nuclei(AGN), the radio galaxy and the colliding galaxies have been searched behind the 8 highest energy events but none are found within $\approx$80 Mpc. No correlation has been identified with the Gamma Ray Bursts (GRB's) .

In order to explain this apparent contradiction, several hypotheses have been proposed to account for the existence of super-GZK cosmic rays. These include

- a decay of super-heavy relic particles or topological defects in the vicinity of our galaxy (top-down scenario),
- a generation of Z^0 particle by the collision of neutrino dark matter with an extremely high energy neutrino in the galactic halo (Z-burst) and
- a breakdown of Lorenz invariance.

There are also abundant ideas proposed to explain the acceleration of EHECR's from the astrophysical point of views (bottom-up scenario).

The history and the present status of EHECR physics were extensively reviewed during the workshop together with the associated subjects in the astrophysics and particle physics.[9]

§2. New Data

In this workshop, what has been new and fresh from the running experiments?

The AGASA reported an update energy spectrum by extending the zenith angle (θ) coverage from previously used 45° to 60° thus extending the acceptance by a factor of 1.5.[10] The number of events with energies more than 10^{20} eV became a total of 15 as opposed to the previous analysis of 8. The energy spectra above and below θ=45° are consistent. The statistical significance of super-GZK cosmic rays is now beyond any doubt, and its confirmation by the newly starting air fluorescence experiment, HiRes, is eagerly awaited.[11]

Another new establishment is the existence of point sources reported by Tinyakov[12] and Takeda.[13] The AGASA had previously reported a clustering of EHECR's, 4 doublets and a triplet, around the GZK cutoff. This time, the angular separation between any two cosmic rays were shown to demonstrate a distinct peak around 0° for both AGASA and Yakutsk with a width consistent with the angular resolution of each experiment. For 59 events from AGASA above $10^{19.6}$ eV, the probability of accidentally producing such a narrow angle correlation from the uniform distribution is less than 10^{-4}. Tinyakov pointed out a possible correlation of clustered events with BL Lacs with $z > 0.1$.[12]

§3. Future Outlook

Several new experiments have been proposed to challenge the enigma of super-GZK events. They are

- Pierre Auger Laboratory[14]
- Telescope Array (TA) Project[15]
- EUSO (Extreme Universe Space Observatory)[16] and
- OWL (Orbiting Wide-angle Light-collectors)[17]

The Auger deploys 1600 water Cherenkov counters in the plain of Argentina and extends the acceptance of AGASA by a factor of 30. The TA uses the ground based air fluorescence telescopes to obtain the same acceptance and aims at identifying the gamma ray primary. The EUSO plans to extend the acceptance far larger than Auger/TA by measuring the air fluorescence from the space station. In the OWL, two wide angle telescopes monitors the atmosphere from 1000 km above the ground.

* Email: fukushim@icrr.u-tokyo.ac.jp

It is well understood that the discrimination between the top-down and the bottom-up scenario can be best achieved by detecting gamma rays or neutrinos above the GZK cutoff.[18] The TA and Auger are able to identify the gamma ray by directly (TA) or indirectly (Auger) measuring the depth of the shower maximum in the atmosphere.

The detection of the near horizontal air shower created by the neutrino is becoming a focus of new large scale air fluorescence detectors. We also had an interesting presentation for the first attempt of detecting the radio Cherenkov wave created at the edge of the Moon by the ZeV neutrino shower.[19] The Auger group is eagerly investigating a method of identifying a horizontal shower by the ground counters.

It should be noted that the large mixing angle between ν_μ and ν_τ obtained by the Super-KAMIOKANDE implies that there must be abundant high energy ν_τ's in the Universe. Such neutrinos could generate a tau particle with high cross section by making the mountain or the crust of the Earth as a target.[20] Generated tau could decay in the air and produce a spectacular horizontal or slightly up-going air shower in the detection volume of the detector. Such a shower will be intensively searched by the new generation detectors.

The EHECR's arriving from a point source are most naturally explained by the bottom-up acceleration scenario. It is particularly so when the astronomical counter part is identified in the sky. If no such counter parts are identified, or the identified origin is very far away from our galaxy, fundamental physics questions would be paused on the nature of such particles which propagates a long distance without being affected by the magnetic field or various types of radiations filling the Universe.[21] The Auger Laboratory with its stable coverage of all the sky in the Southern hemisphere in a few years, and the Northern hemisphere in near future together with TA, would produce an exciting data for numerous point sources of EHECR's.

In Summary, the keywords of the new generation experiments are;

1. The large acceptance,
2. The gamma ray and neutrino identification,
3. The point source resolution and
4. The precise determination of energy spectrum.

The Fig.1 shows the progress of the air shower experiments with time. It is almost certain that the origin of the super-GZK cosmic rays will be unveiled by the new experiments in the first decade of this century.

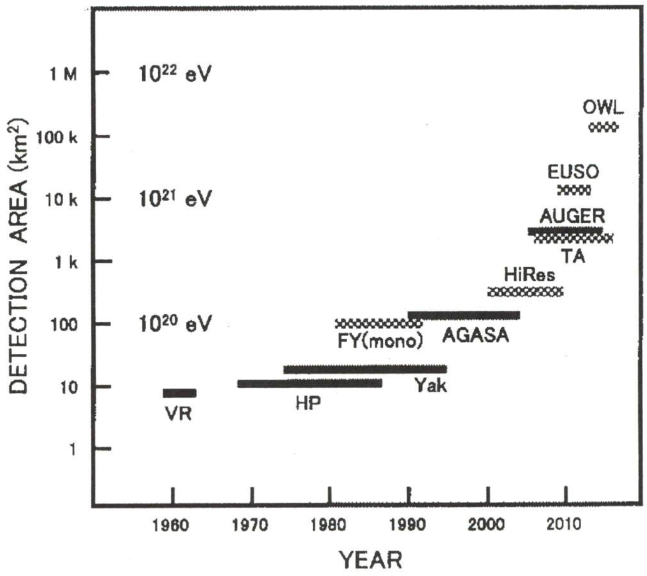

Fig. 1. The increase of the covered ground area with time for the past, present and future EHECR detectors. Approximate energy limit of the investigation is also shown in the ordinate.

1) J. Linsley: Phys. Rev. Lett. **10** (1963) 146.
2) M. A. Lawrence, R. J. O. Reid and A. A. Watson: J. Phys. G: Nucl. Part. Phys. **17** (1991) 733.
3) B. N. Afanasiev et al.: *Proceedings of the Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays*, p.35, edited by M. Nagano,1993.
4) D. J. Bird et al.: Phys. Rev. Lett. **71** (1993) 3401.
5) M. Takeda et al.: Phys. Rev. Lett. **81** (1998) 1163.
6) N. Hayashida et al.: Astrophys. J. **522** (1999) 225.
7) K. Greisen: Phys. Rev. Lett. **16** (1966) 748.
8) T. Zatsepin and V. A. Kuzmin: JETP Lett. **4** (1966) 178.
9) Proceedings of this workshop. A comprehensive review of the experiments and theories of the extremely high energy cosmic rays is recently given by M. Nagano and A. A. Watson: Rev. of Mod. Phys. **72** (2000) 689.
10) N. Sakaki: Proceedings of this workshop.
11) L. Wincke: Proceedings of this workshop.
12) P. Tinyakov: Proceedings of this workshop.
13) M. Takeda: Proceedings of this workshop.
14) M. Boratav and P. Sommers: Proceedings of this workshop. See also *The Pierre Auger Observatory Design Report, Second edition*, March 1997, available by the web http://www.auger.org/admin.
15) M.Sasaki, K. Martens and T.Yamamoto: Proceedings of this workshop. See also *The Telescope Array Design Report* July 2000, available by the web http://www-ta.icrr.u-tokyo.ac.jp.
16) L. Scarsi, H. Shimuzu and O. Catalano: Proceedings of this workshop. See also *EUSO (Extreme Universe Space Observatory), a Proposal for the ESA F2/F3 Flexible Missions*, available by the web http://euso.riken.go.jp.
17) Y. Takahashi: Proceedings of this workshop.
18) A. Olinto: Proceedings of this workshop.
19) P. Gorham: Proceedings of this workshop.
20) D. Fargion: Proceedings of this workshop.
21) F. Sato: Proceedings of this workshop.