AGASA RESULTS AND THE STATUS OF TA

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The Akeno Giant Air Shower Array (AGASA) had observed 11 events of Extremely-High Energy Cosmic Rays (EHECRs) with energies exceeding 10^{20}eV. The energy of these cosmic rays is beyond the Gleisen-Zatsepin-Kuzmin (GZK) cutoff expected by the interaction of EHE protons with the Cosmic Microwave Background (CMB). New experiments with much larger acceptance and improved energy determination, Telescope Array (TA) experiment and Pierre Auger observatory are being built to confirm the existence of EHECRs and to understand their origin.

1. Super-GZK Cosmic Rays

The AGASA reported that the rate of observing EHECRs exceeding 10^{20} eV was consistent with a continued spectrum with a power law of $E^{-2.7}$ and the expected GZK-cutoff structure[1] was not observed. The Fly's Eye air fluorescence telescope also reported an event with 3×10^{20} eV in 1994[2].

High energy astronomical objects such as the active galactic nuclei and radio galaxies were searched as a possible origin of such EHECRs, but none were found in the arrival direction of these events within 100 Mpc of our galaxy[3]. More distant origins may be considered, but only if a special mechanism to allow a longer propagation of EHECRs to take place, for example the violation of special relativity[4] or the EHE neutrinos as the carrier of such energy[5].

It was therefore conceived that super-GZK ($E > 10^{20}$ eV) cosmic rays may be generated by the decay of super-heavy particles in the nearby uni-

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[*] On behalf of Telescope Array collaboration

verse. Particles with energy $> 10^{20}$ eV are easily produced if the mass of the particle is at the Grand Unification scale. Such super-heavy particles may be surviving as a relic of the Big Bang or presently generated by the decay of topological defects[6]. An abundant generation of EHE gamma rays and neutrinos, in place of protons and nuclei, is characteristic in the decay of such particles.

2. Overview of TA

The Telescope Array (TA) was thus proposed in 2000[7] in order to investigate the origin of super-GZK cosmic rays by employing a large array of fluorescence telescopes with ~100 times larger acceptance than AGASA.

The HiRes experiment, however, presented an energy spectrum indicating the existence of the cutoff in the 27th ICRC and the result was later published in 2003[8]. The HiRes spectrum was composed of two monocular spectra each obtained by a single telescope. A preliminary stereo spectrum was presented in 2005 at the 29th ICRC[9]; it exhibits a clear cutoff but the E^3 multiplied flux below $10^{19.5}$ eV is larger than the monocular flux by a factor of ~1.5.

With contradictory results appearing from AGASA and HiRes, it became urgent to understand the experimental bias in the energy and the acceptance determination of two experiments. The construction of full TA is thus deferred, and we decided to build a composite detector at first with AGASA-like ground array and TA fluorescence telescopes[10]. We call it as phase-1 TA (ph-1 TA). We expect that simultaneous measurement of the same EHECRs by two detectors will reveal systematics of two methods and will guide us to a reliable determination of the primary energy and the acceptance.

The phase-1 TA consists of a large plastic scintillator array and 3 stations of air fluorescence telescopes overlooking the array from periphery as shown in Fig.1. The ground array has an aperture of ~1200 km^2 sr, which is an order of magnitude larger than that of AGASA. The fluorescence telescope will have a stereoscopic aperture of ~300 km^2 sr at 10^{20} eV with 10% duty factor. The telescope will also supply information on the primary particle species by measuring the longitudinal shower profile. It will be built in the West Desert of Utah, 140 miles south of Salt Lake City (lat. 39.3°N, long. 112.9°W, alt. ~1400 m).

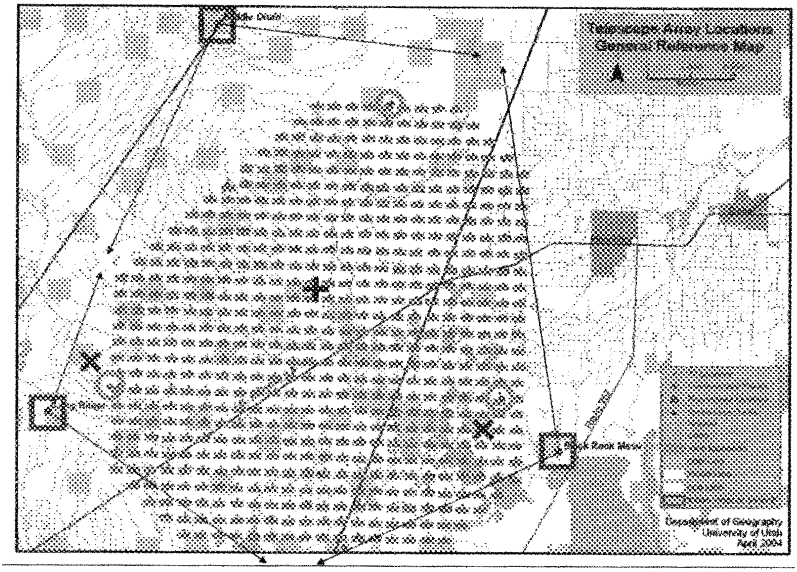

Figure 1. Detector Arrangement of ph-1 TA. The surface detector locations are indicated by small numbers. The fluorescence telescope stations are marked by square boxes.

3. Ground Array of ph-1 TA

The ground detector consists of 576 plastic scintillators deployed in a grid of 1.2 km spacing. It covers the ground area of ~760 km^2. Approximately 80% of them will be on the Federal land, ~10% on the state trust land and the rest on privately owned land. The detection (trigger) efficiency is ~100% for cosmic rays with energies more than $10^{19.5}$ eV with zenith angle less than 45°.

The counter is composed of two layers of plastic scintillator overlaid on top of each other. The scintillator (CI, CIMS-G2) is 1.2 cm thick, 3 m^2 large and is read out by 96 wave length shifter fibers installed in a groove on the surface. The fiber (Kuraray, Y-11(200)M) has a diameter of 1 mm and a length of 5 m. Both ends of the fiber are optically connected to the photomultiplier (Electron Tube 9124B). A passage of cosmic ray muon gives ~15 photo-electrons in average. Two layers are used for the coincidence measurement, for the muon calibration trigger and for extending the dynamic range by setting different PMT gains for two counters.

The signal from each PMT is continuously digitized with a 12-bit flash ADC with 50 MHz sampling. When both of the PMTs record more than 1/3 of the muon signal, wave forms of ~2.5 μs duration are stored with a time stamp supplied by the GPS. This rate of local buffering is less than 1 kHz. The relative timing between remotely separated counters will be controlled with better than ±20 ns accuracy by the GPS, which is sufficient to supply good resolution for the determination of the arrival direction.

When one of the PMT signals exceeds a trigger threshold of 3 muons, its timing is recorded in a local trigger list. The content of the list is transmitted to a branch DAQ board by the wireless LAN at 1 Hz. The list may contain less than 100 events for normal counters. The branch DAQ board is installed on a communication tower built at the periphery of the array. Three towers of ~15 m high will be built for the communication up to ~20 km. An air shower event is identified by the branch DAQ firmware by requiring clustered hits with a good coincidence timing. The air shower event rate will be less than 1 Hz when at least 3 adjacent counters are required in coincidence.

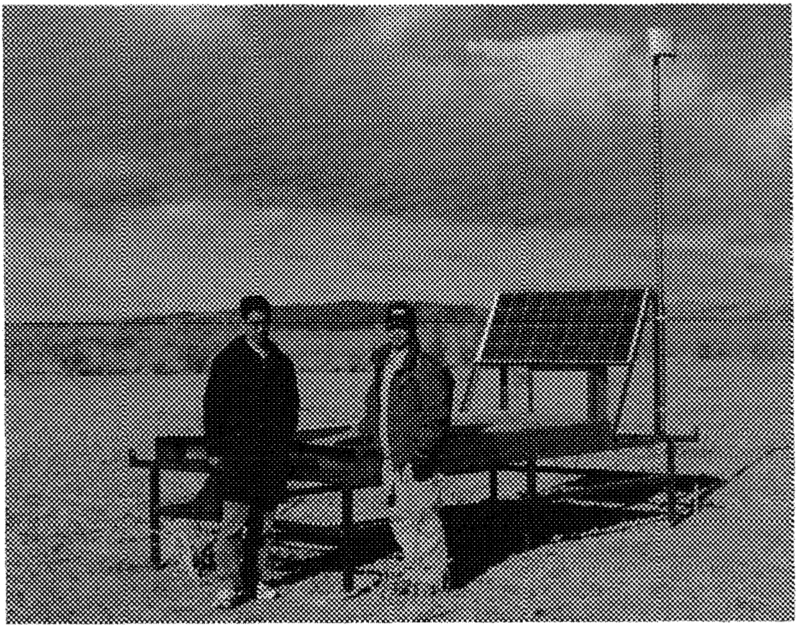

Figure 2. One of the Deployed Surface Detectors.

When an air shower trigger is generated in a branch DAQ board, a command is broadcasted to all counters and relevant counters storing the event with good coincidence timing respond by transmitting the wave form data to the branch DAQ board. The data are then transmitted to a central DAQ system via tower to tower wireless communication and stored in a mass storage. We employ a commercially produced wireless transmitter with the maximum speed of 11 Mbps using 2.4 GHz spread spectrum technology. The dead-time-less DAQ operation is aimed with the high transmission speed together with a large buffering memory at each counter.

One of the counters test-deployed to the field in December 2004 is shown in Fig.2. The total electrical power consumed by the PMT, ADC, GPS and LAN is approximately 7 W and is locally generated by the solar panel of ~120 W capacity (Kyocera KC-120J, see Fig.2). Behind the panel will be a heat-insulated enclosure containing a backup battery (12V, ~65 Ah and deep cycle) and all the electronics. A communication antenna is fixed at the top of 3.3 m tall mast. The total weight of the counter is less than 250 kg, such that it can be easily deployed by helicopter without disturbing the wilderness environment.

4. Fluorescence Telescope

Twelve reflecting telescopes are installed at each station and cover the sky of $3^\circ - 34^\circ$ in elevation and 108° in azimuth looking toward the center of the ground array (see Fig.3). The field of view of each telescope is 18.0° in azimuth and 15.5° in elevation. A spherical dish of 6.8 m^2 is composed of 18 hexagonal mirrors with a radius of curvature of 6067 mm. The direction of each mirror is individually adjustable and a spot size of less than 20 mm in diameter is realized at the focal plane (2960 mm). The mirror is made by 10.5 mm thick high thermal resistivity glass (Schott Borofloat) and is aluminum coated by vacuum deposition. The surface of the aluminum is protected by producing a ~50 nm thick anodization layer.

The air shower image is detected by a mosaic PMT camera on the focal plane. A set of 16×16 PMTs (Hamamatsu 6234) with a hexagonal window is used for one camera. Each PMT covers $1.1^\circ \times 1.0^\circ$ patch of the sky. A UV transmitting glass filter (Schott BG3, 4 mm thick) is attached in front of each PMT for blocking the night sky background in the visible light range. The whole camera is assembled in a chassis with a window made by a UV transparent plexiglass.

Negative high voltage is applied to the PMT by a bleeder circuit using zener diodes to ensure a stable operation under high night sky background. The high voltage is individually adjustable for all PMTs. With a PMT gain

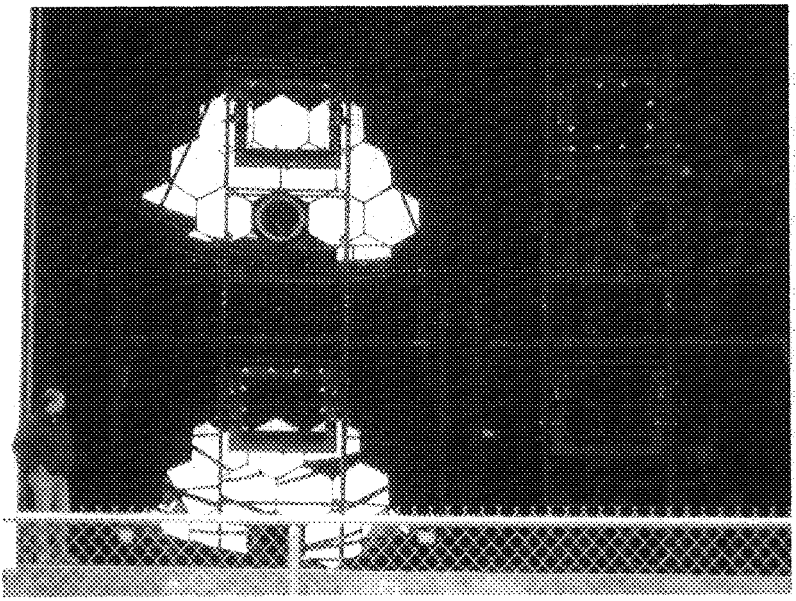

Figure 3. Fluorescence Telescopes of TA

of $\sim 10^5$, a linearity of up to 32 k photoelectrons in 100 ns is achieved. A signal from the PMT is amplified by a factor of 50 by the pre-amplifier and is sent to a Signal Digitizer and Finder (SDF) with 25 m twisted pair cable. The SDF module receives the signal with a shaping filter and digitizes it with a 12-bit, 40 MHz FADC. Consecutive 4 samplings are added by the following FPGA. A trace of fluorescence signal is searched in pipeline at the FPGA employing a sliding sum algorithm for every 25.6 μs of the time window. The dc component from the night sky background is estimated every 1 ms and is subtracted. The SDF is a 9U VME module and 16 channels are mounted in one module.

The result of the "hit" search by the SDF is reported to a Track Finder (TF) in the same VME crate and an air shower track is searched in one camera. A track is found when 5 or more than 5 adjacent PMTs are fired. A looser track definition is applied to a camera-crossing event. The results of all TF modules are concentrated to a Central Trigger Decision (CTD) module and the decision of data acquisition is made. The wave form data stored in the SDF memory are read out to "a camera PC" in parallel and a complete event is subsequently built from the camera PCs by Ethernet.

The calibration of telescope sensitivity and the measurement of atmospheric correction are essential for obtaining an accurate cosmic ray energy. They are described in references[11].

5. Prospects

The phase-1 TA is being built by the collaboration of Japanese and American physicists. The group consists of physicists who have been working in AGASA, HiRes and HEP experiments in the US and Japan. The Japanese fund for ph-1 TA was approved in 2003 by the Grants-in-Aid for Scientific Research (Kakenhi) of Priority Areas. The US group has submitted a proposal for matching fund to the NSF in 2005. The US proposal includes a construction of TALE, a Low Energy extension of TA down to 10^{17} eV, to investigate the modulation of CR composition and spectrum expected by the galactic to extra-galactic transition of CR origins. The infrastructure of TA and TALE in Utah is also the responsibility of the US group.

As of December 2005, a total of 370 surface detectors were produced, of which 18 were test-deployed in the field in 2004. We plan to build communication towers and deploy the rest of counters into the field when the land use permit by the Bureau of Land Management (BLM) is granted, which is expected in February, 2006.[a] The first fluorescence station was built and 12 telescope frames were installed, of which two were equipped with mirrors and a test observation was made with prototype camera and electronics in July, 2005. We expect to complete the construction of TA in April, 2007 and start taking data.

The Pierre Auger group is constructing a large hybrid experiment in Argentina with 1600 water tank detectors. The construction will be complete by the end of 2006. The group presented the first EHECR spectrum at the 29th ICRC in August, 2005 using an exposure already larger than what AGASA had accumulated in 13 years of operation. There was no event exceeding 10^{20} eV. The group considers, however, premature to conclude the existence of GZK-cutoff because the present systematic error of energy determination is estimated to be 50% at 10^{20}eV. The Auger group calibrated the ground array energy estimator $\rho(1000)$, the muon density 1000 m away from the shower center, by the measurement of shower energy from the fluorescence telescope. The extrapolation of the calibration from the lower energy, where most of the hybrid events were collected, caused the major part of the systematic error.

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[a] The BLM grant was obtained in May 2006.

The construction of ph-1 TA will be finished a few months after the Pierre Auger is completed in Argentina. The acceptance of Auger ground array is ∼4.5 times larger than that of ph-1 TA assuming the same zenithal acceptance. The scintillator of TA counts the number of penetrating charged particles and it is dominated by the electrons which outnumber the muons by an order of magnitude. The water tank of Auger on the other hand is more sensitive to the penetrating high energy muons rather than the soft electrons which stop near the surface of the water tank and do not generate as many Cherenkov photons.

The energy measurement of ph-1 TA therefore is less sensitive to the unknown particle composition of primary cosmic rays and the details of hadronic interactions at EHE, whereas its sensitivity for determining the primary particle species using the muon content is severely limited. The identification of EHE gamma rays and neutrinos will be difficult. It is our belief that the characteristic features of ph-1 TA, the sampling of electromagnetic shower energy, the unique calibration of fluorescence generation and the measurement in the Northern Hemisphere, will make an essential contribution to the understanding of the intricate problem of GZK cutoff.

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