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HIGH ENERGY COSMIC RAY DIVISION

Overview

Three major research activities of the High Energy Cosmic Ray Division are the study of very high energy gamma rays by the CANGAROO group, extremely high energy cosmic rays by the Telescope Array (TA) group, and very high energy cosmic rays and gamma rays by the Tibet ASγ Collaboration. Other activities, such as experiments utilizing the Akeno observatory, the Norikura observatory, the Mt. Chacaltaya observatory (jointly operated with Bolivia), and the emulsion-pouring facilities are closely related to inter-university joint research programs. Also an all-sky high resolution air-shower detector (Ashra) has been installed on the Hawaii island. The High Energy Astrophysics Group was newly-created in this fiscal year and aims to explore various high energy astrophysical phenomena, mainly by theoretical approaches.

The CANGAROO project (Collaboration of Australia and Nippon for a GAmma-Ray Observatory in the Outback) is a set of large imaging atmospheric Cherenkov telescopes to make a precise observation of high-energy air showers originated by TeV gamma rays. It started as a single telescope with a relatively small mirror (3.8 m in diameter) in 1992. In 1999 a new telescope with a 7-m reflector has been built, and now it has a 10-m reflector with a fine pixel camera. The main purpose of this project is to explore the violent, non-thermal universe and to reveal the origin of cosmic rays. An array of four 10-m telescopes has been completed in March 2004 so that more sensitive observations of gamma rays are realized with its stereoscopic imaging capability of Cherenkov light. Several gamma-ray sources have been detected in the southern sky and detailed studies of these sources are now ongoing.

At the Akeno observatory, a series of air shower arrays of increasing geometrical sizes were constructed and operated to observe extremely high energy cosmic rays (EHECRs). The Akeno Giant Air Shower Array (AGASA) was operated from 1991 to January 2004 and covered the ground area of 100 km^2 as the world largest air shower array. In 13 years of operation, AGASA observed a handful of cosmic rays exceeding the theoretical energy end point of the extra-galactic cosmic rays (GZK cutoff) at 10^{20} eV. The Telescope Array (TA), a large plastic scintillator array with air fluorescence telescopes, has been constructed in Utah, USA, which succeeds AGASA and measures the EHECRs with an order of magnitude larger aperture than that of AGASA to unveil the origin of super-GZK cosmic rays discovered by AGASA. The TA started full operation as the largest EHECR detector viewing the northern sky in 2008.

An air shower experiment aiming to search for celestial gamma-ray point sources started in 1990 with Chinese physicists at Yangbajing (Tibet, 4,300 m a.s.l.) and has been successful. This international collaboration is called the Tibet ASγ Collaboration. An extension of the air shower array was completed in 1995 and an emulsion chamber has been combined with this air shower array since 1996 to study the primary cosmic rays around the knee energy region. After successive extensions carried out in 1999, 2002 and 2003, the total area of the air shower array amounts to 37,000 m^2. The sun's shadow in cosmic rays affected by the solar magnetic field was observed for the first time in 1992, utilizing its good angular resolution at multi-TeV energy region. From this experiment with better statistics, we expect new information to be obtained on the large-scale structure of the solar and interplanetary magnetic field and its time variation due to the 11-year-period solar activities.

A new type of detector, called Ashra (all-sky survey high resolution air-shower detector), was developed. The first-phase stations were installed near the Mauna Loa summit in the Hawaii Island and high-efficiency observation is continuing. It monitors optical and particle radiation from high-energy transient objects with a wide field-of-view.

The High Energy Astrophysics group is conducting theoretical researches on fundamental processes responsible for nonthermal particle acceleration in various astrophysical environments, including first-order diffusive shock acceleration, second order stochastic acceleration in shock downstream regions, modification of shock structure by pick-up interstellar neutrals, as well as injection processes of suprathermal particles. In addition to these theoretical works, R/D studies for radio observations of pulsars and cosmic ray air showers are also being made.

TA: Telescope Array Experiment

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Overview and Status of TA

The TA [1] is the detector that consists of the surface array of plastic scintillator detectors (a la AGASA) and fluorescence detectors (a la HiRes). The aim of the TA is to explore the origin of extremely-high energy (EHE) cosmic rays by measuring energy, arrival direction and mass composition. It is located in the West Desert of Utah, 140 miles south of Salt Lake City (lat. 39.3°N, long. 112.9°W, alt. ~1400 m). The construction of the TA was performed mainly by the Grants-in-Aid for Scientific Research (Kakenhi) of Priority Areas "The Origin of Highest Energy Cosmic Rays" (JFY2003-JFY2008) and the US National Science Foundation (NSF). All the three fluorescence stations started the observation in November 2007. Major construction of the surface detector array was completed in February 2007, and the array of the surface detectors started the full operation in March 2008. The TA is operated by the international collaboration of researchers from US, Russia, Korea and Japan. The main fund for the TA operation is the Grants-in-Aid for Scientific Research (Kakenhi) of Specially Promoted Research "Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays" (JFY2009-JFY2013).

Surface Detector Array

The surface detector (SD) array consists of 507 plastic scintillators on a grid of 1.2 km spacing. It covers the ground area of about 700 km^2.

The counter is composed of two layers of plastic scintillator overlaid on top of each other. One layer of scintillator is 1.2 cm thick and 3 m^2 in area. Light from each layer is collected by 104 wave length shifter fibers 5 m long, which are installed in grooves on the surface. Both ends of the fibers are bundled and optically connected to one photomultiplier for each layer. Power of each SD is supplied by a solar panel and battery. The communication between SDs and the host at the communication tower is performed by wireless LAN.

Fluorescence Telescope

The TA has three fluorescence detector (FD) stations. The fluorescence station in the southeast is located at the Black Rock Mesa (BRM) site. The southwestern station is located at the Long Ridge (LR) site and the station in the north is located at the Middle Drum (MD) site.

Twelve reflecting telescopes were newly constructed and installed at each of the BRM and LR stations and cover the sky of 3°-34° in elevation and 108° in azimuth looking toward the center of the surface detector array.

The MD station was constructed using refurbished equipment from the old HiRes-1 observatory. Fourteen reflecting telescopes cover the sky of 3°-31° in elevation and 114° in azimuth.

We also built a laser shooting facility (Central Laser Facility: CLF), which is located at an equal-distance (21 km) from three fluorescence stations for atmospheric monitor. The Rayleigh scattering at high altitude can be considered as "standard candle" observable at all the stations.

A LIDAR (LIght Detection And Ranging) system located at the BRM station is used for the atmospheric monitoring. It consists of a pulsed Nd:YAG laser and a telescope attached to an alto-azimuth. The back-scattered light is received by the telescope to analyze the extinction coefficient along the path of the laser.

For monitoring the cloud in the night sky, we installed an infra-red CCD camera at the BRM station, and take data of the night sky every hour during FD observation.

In order to confirm absolute energy scale of the fluorescence detector in situ, we installed a compact electron linear accelerator (Electron Light Source: ELS) [2] at the BRM FD site. A beam of 10^9 electrons with energy of 40 MeV and a duration of 1 μs well simulates a shower energy deposition of $\sim 4\times10^{16}$ eV 100 m away from the station, which corresponds to a shower of $\sim 4\times10^{20}$ eV 10 km away. The calibration is performed by comparing the observed fluorescence signal with the expected energy deposition calculated by the GEANT simulation [3]. We began to start up the ELS in June 2010, and we shot electron beam vertically up into the atmosphere from the ELS for the first time and took the images with FD on September 3rd, 2010. Fig. 1 shows the image of the pseudo shower by the electron beam together with the image by Geant MC simulation.

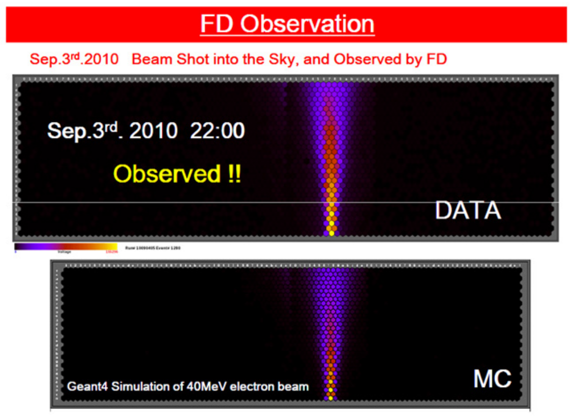

Fig. 1. The image of the pseudo shower by the electron beam that was shot from the ELS at the BRM FD site for the first time on September 3rd, 2010 (upper). The image by Geant MC simulation (lower).

Status of TA Observation

Fig. 2 shows the rate of operation of the surface detectors from May 2008 through March 2011. There were periods for which the fraction of operation decreased because of maintenance and bad weather. The average rate of operation is close to 100%.

Fig. 3 shows the observation hours for the BRM and LR fluorescence detectors from November 2007 through February 2011. We observe during moonless night, and the observation time per night in winter is longer than that in summer.

Energy spectrum

The Auger group and the HiRes group published the results of energy spectrum, which are consistent with GZK cutoff with their energy scales determined by the method of fluorescence telescope [4, 5]. We present energy spectra using

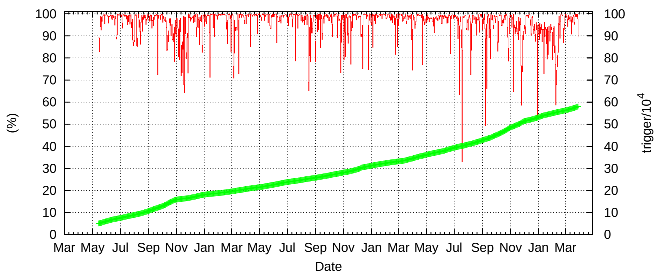

Fig. 2. The rate of operation of the surface detectors in red and the integrated number of triggered air shower events in green from March 2008 through March 2011.

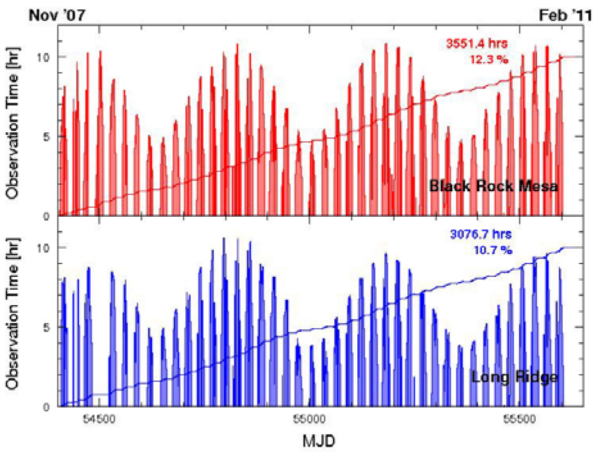

Fig. 3. Observation hours per night and integrated observation hours for the BRM (upper) and LR (lower) fluorescence detector sites from November 2007 through February 2011. The horizontal axes represent modified Julius day (MJD).

three different methods: the MD monocular FD analysis, hybrid analysis, and SD analysis.

Energy spectrum by the MD monocular FD analysis

The analysis of monocular FD data at the MD station provides a direct comparison between the TA and HiRes energy spectra. The MD spectrum uses the data collected over a three-year period between December 2007 and September 2010. The MD spectrum is based on the monocular observation technique and is analyzed using the profile-constrained geometry reconstruction technique developed by the HiRes-1. The preliminary monocular energy spectrum from the MD fluorescence detector is shown in Fig. 4. The TA MD monocular energy spectrum is in good agreement with the HiRes spectra. The details of the analysis of the MD FD data is described in [6].

Energy spectrum by hybrid analysis

The hybrid events which are detected both by FD and SD are useful to compare the reconstructed results from FD and SD. In addition, we improve the reconstruction of FD events more precisely by using information both of FD and SD for hybrid events than FD monocular analysis alone. Here we use timing information from one SD. When we use only data of the fluorescence detectors, the aperture depends on energy of primary cosmic rays, but hybrid analysis has the merit that the

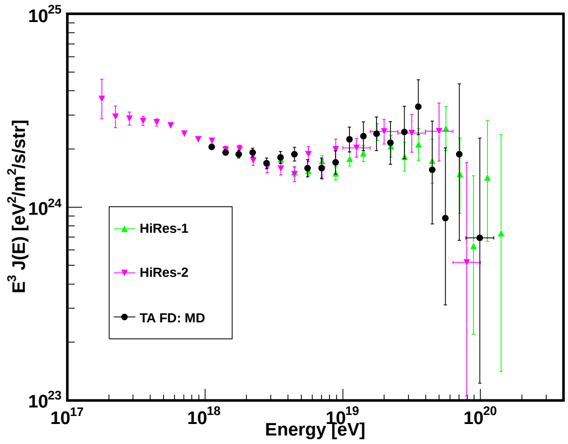

Fig. 4. The preliminary monocular energy spectrum from the TA MD fluorescence detector (black circles). Red circles and blue circles represent those for the HiRes-1 and HiRes-2 detectors, respectively.

aperture is kept constant above 10^{19} eV by the size of the surface detector array and the systematic error of the aperture becomes smaller. The hybrid event candidates were searched for by the condition that the trigger time difference between FD and SD is less than 200 μs from May 2008 through September 2009. We found 1978 hybrid events. The effective aperture after the quality cuts is obtained from the Monte Carlo simulation code COSMOS [7] with QGSJET-II model for pure proton including calibration factors for the whole period. The exposure of the hybrid analysis is approximately 4×10^{15} m^2 sr s above 10^{19} eV. After the reconstruction procedure, 124 events remain above $10^{18.65}$ eV. The total systematic uncertainties are 19% in energy measurement, and 10% in flux from cloud monitoring. The preliminary energy spectrum from the hybrid analysis is shown in Fig. 5. The energy spectrum by this analysis is consistent with the other TA results. The details of the hybrid analysis are described in [8].

Energy spectrum by using the data of the surface detectors

We measure the energy spectrum by using the SD data from May 2008 through February 2010. The exposure is approximately 1500 km^2 sr yr which is equivalent to the total exposure of the AGASA.

There are two types of fits in SD event reconstruction: the fit to determine the geometry of the shower and the fit to determine the lateral density distribution. Monte Carlo data were generated by CORSIKA air shower simulation program [9] with QGSJET-II proton model. The detector simulation with front-end electronics and trigger was constructed with Geant4 simulation. The fit result of the Monte Carlo data by the parameters tuned by the data is also good in the same way as that of the data.

The basic idea of the energy reconstruction is to use the charge density at a distance of 800 m from shower core (S_{800}) as an energy estimator. The correlation of S_{800} and zenith angle with primary energy from Monte Carlo study is used for the first estimation of the primary energy of the data.

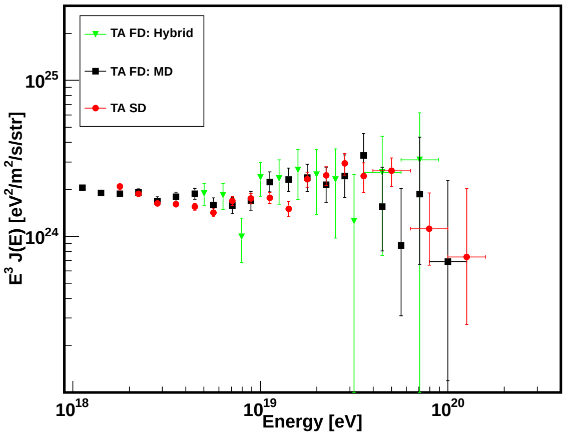

Fig. 5. The preliminary TA energy spectra measured by three different methods. Green downward triangles denote the spectrum by hybrid analysis. Black squares denote the spectrum by the MD monocular FD analysis. Red circles denote the spectrum by the data of the surface detectors with "energy scaled to FD energy".

We compare the energy scales of FD and SD using hybrid events. The scatter plot of the energies of well-reconstructed 331 events is shown in Fig. 6. It shows that the energy of SD is 27% larger than that of FD. We choose the energy scale of FD, and the SD energy is rescaled by 27%.

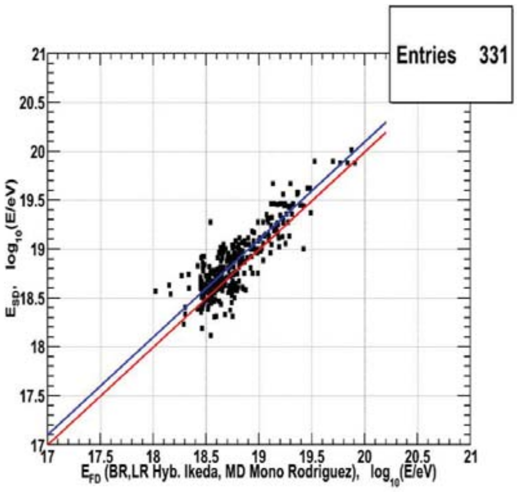

Fig. 6. The preliminary result of the comparison of the energies between FD and SD. The red line corresponds to $E_{SD} = E_{FD}$. The blue line corresponds to $E_{SD} = 1.27 \times E_{FD}$.

After the reconstruction procedure, 6264 events with zenith angles below 45° remain. We obtain the energy spectrum from the number of events in each energy bin by using the effective aperture obtained from the Monte Carlo data. The preliminary energy spectrum is shown in Fig. 5. An excess of UHECRs exceeding the prediction by GZK, which had been observed by AGASA in 1998, was not confirmed. We performed a fit using power laws in three regions, and found the two breaks at log$E$ (E in eV) of 19.75 and 18.71, which correspond to the GZK suppression [10, 11] and the ankle, respectively. We observed five events above the break point at $10^{19.75}$ eV while the expected number of events along the continuous spectrum is 18.4. This result provides evidence for the flux suppression with the significance of 3.5σ. The details of the SD analysis are described in [12].

The obtained preliminary energy spectra by three different methods from the TA experiment are shown together with other experiments in Fig. 7.

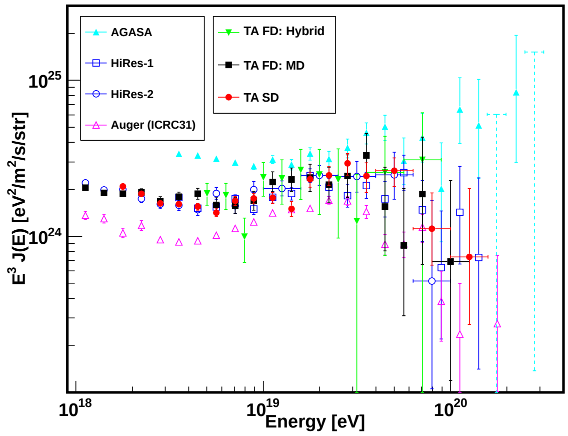

Fig. 7. The preliminary spectra from the Telescope Array together with the spectra from other experiments. The green closed downward triangles represent the TA hybrid spectrum, the black closed squares the monocular FD spectrum from the MD station, and the red closed circles the TA SD spectrum. The light-blue closed triangles represent the AGASA spectrum, the blue open squares the HiRes-1 spectrum, the blue open circles the HiRes-2 spectrum, and the purple open triangles the PAO spectrum. The light-blue dotted bars are 90% C.L. upper limits for the AGASA.

Measurement of mass composition by shower maximum depth ($X_{\max}$)

The basic idea to determine the mass composition of UHECRs is to use the dependence of the atmospheric depth of shower maximum on the primary energy and mass composition.

For composition in EHE region, the Auger data suggests a change to a heavier composition [13] while the HiRes data is consistent with constant elongation rate which stays with proton [14].

The data set from November 2007 through September 2010 is used in this analysis. The events observed simultaneously at two new FD stations are analyzed for the shower geometry by stereo technique and for the longitudinal development in the same way as hybrid technique to measure the atmospheric depth of shower maximum ($X_{\max}$).

The Monte Carlo data are generated by CORSIKA with the particle types of proton and iron, and the interaction models of QGSJET-01 and SIBYLL. The resolution of energy is 8% and that of $X_{\max}$ is 23 g/cm^2 at energy around $10^{19.0}$ eV from QGSJET-01 proton Monte Carlo simulation. We notice that the measured $X_{\max}$ has a bias from the limit of the field of view. Since this bias also depends on the model, the reconstructed $X_{\max}$ from the observed data and Monte Carlo data are compared by applying the same analysis procedure. An example of the distribution of $X_{\max}$ for the TA stereo data along with QGSJET-01 Monte Carlo data is shown in Fig. 8. The distribution of $X_{\max}$ of the observed data is in good agreement with that of the Monte Carlo data for protons.

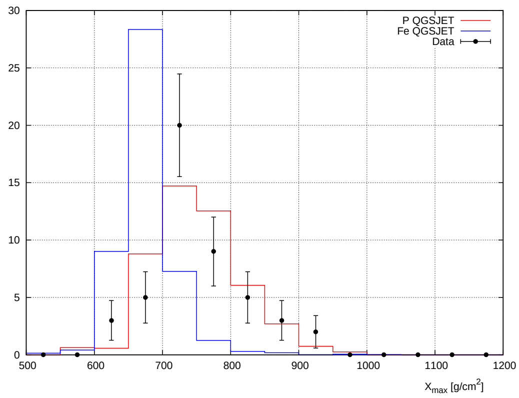

Fig. 8. The preliminary reconstructed $X_{\max}$ distribution for the TA stereo data (points) along with QGSJET-01 Monte Carlo data in the energy region from $10^{18.8}$ to $10^{19.0}$ eV. The red and blue histograms are the proton and iron predictions, respectively.

The evolution of the average $X_{\max}$ with energy was measured and compared with the Monte Carlo data in the energy range from $10^{18.2}$ to $10^{20.0}$ eV as shown in Fig. 9. The observed TA data are in good agreement with the QGSJET-01 pure proton prediction. The details of the mass composition study are described in [15].

Search for UHE photons

Several models were proposed for the interpretation of the origin of highest energy cosmic rays. There is a possibility that cosmic rays were generated and accelerated in very active region up to highest energy cosmic rays (bottom-up model), and were observed at the earth through GZK process. If highest energy cosmic rays are generated and accelerated at the sources such as AGN, there is a possibility that UHE photons with energy around 10^{19} eV are generated by resonant π^0 production in GZK-type process. It is also expected that large amount of UHE photons with energy above 10^{19} eV could be generated by non-accelerated model (top-down model) such as unknown super-heavy particles. It is expected that UHE photons with energy above 10^{19} eV interact in deeper atmosphere than UHE hadrons. Then the curvature of air shower front of photons around the ground is larger than that of hadrons.

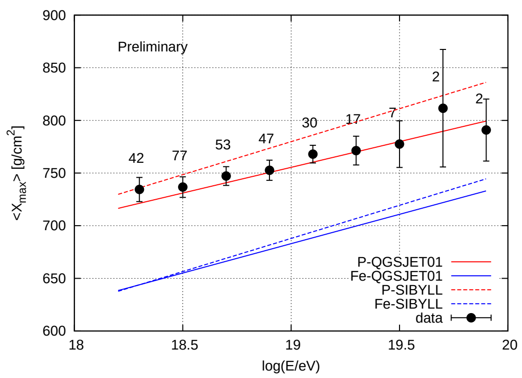

Fig. 9. The preliminary result of the average reconstructed $X_{\max}$ as a function of energy. The black points are the TA stereo data. The upper set of red lines are predictions for pure protons with the interaction models of QGSJET-01 (solid line) and SIBYLL (dashed line). The lower set of blue lines are under the assumption of iron.

Fig. 10 shows the curvature of air shower front for the data of the surface detectors taken from May 2008 through October 2009. We obtained the limit on the integral flux of photons with energy above 10^{19} eV to be

$$3.4 \times 10^{-2}\ km^{-2} sr^{-1} yr^{-1}$$

at 95% confidence level as shown in Fig. 11 [16].

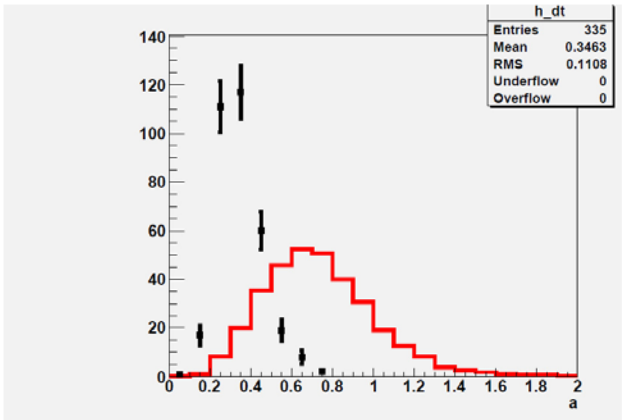

Fig. 10. The preliminary result of the distribution of the curvature of shower front of UHE cosmic rays (Linsley curvature parameter) for zenith angle from 45° to 60°. Black points denote the distribution of curvature of the TA data. The histogram corresponds to the expected distribution of the curvatures for the photons that are generated by the spectrum with power index of -2.

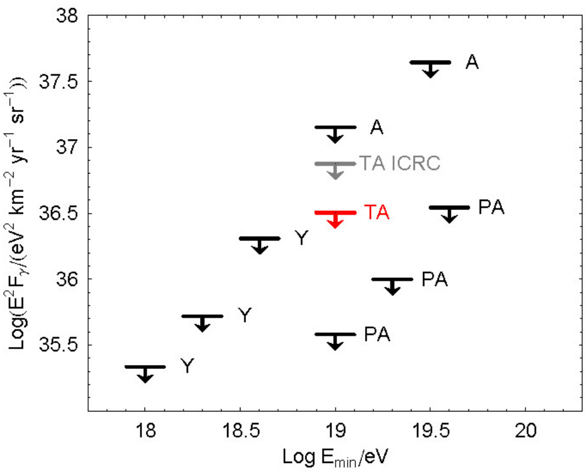

Fig. 11. Upper limits on the integral flux of UHE photons for different experiments: the latest preliminary TA result (TA) in red, TA at ICRC09 (TA ICRC) in gray, AGASA (A), Auger (PA), and Yakutsk (Y).

Arrival directions of UHE cosmic rays

We present the analysis of UHECRs for correlations with the large-scale structure (LSS), correlations with AGN and small-scale anisotropy. The analysis is based on the SD data collected for zenith angles less than 45° from March 2008 through September 2010.

Correlations with LSS

At large angular scales, the anisotropy in the PAO data was claimed [17], and that in the HiRes data was not confirmed [18].

We use the 2MASS Galaxy Redshift Catalog (XSCz) [19] that is derived from the 2MASS Extended Source Catalog (XSC) with redshifts that have either been derived from the 2MASS photometric measurements or measured spectroscopically. We use the galaxies at distances from 5 to 250 Mpc and with Ks magnitudes less than 12.5. This catalog provides the most accurate information about three-dimensional galaxy distribution. We assume that UHECRs are protons. We also assume that the effects of the Galactic and extragalactic magnetic fields are approximated by a Gaussian smearing angle. The flux map calculated with these assumptions at the energy threshold of 57 EeV is shown in Fig. 12. The rectangular region around the Galactic center ($|b| < 10°$ and $|l| < 90°$) is excluded from the analysis because the underlying galaxy catalog is incomplete. We choose an a priori confidence level of 95%, which means that the two distributions are incompatible at the 95% C.L. if the KS-test probability (p-value) is smaller than 0.05. The data both above 40 EeV and 57 EeV are compatible with LSS model. For isotropic model, the data above 40 EeV are compatible while the data above 57 EeV are incompatible at the 95% C.L. [20, 21]

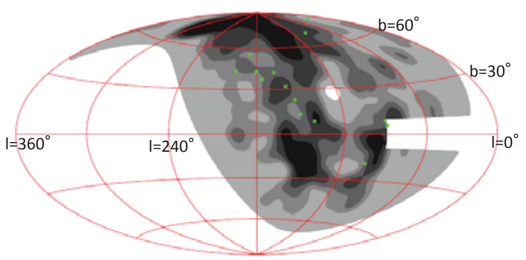

Fig. 12. The sky map of expected flux from LSS model together with observed arrival directions of UHECRs with energies above 57 EeV (green points) in the Galactic coordinates. Darker gray region indicates larger flux and each band contains 1/5 of the total flux. The region $|b| < 10°$ and $|l| < 90°$ is excluded from the analysis. The smearing angle is 6°.

Correlations with AGN

The Pierre Auger Collaboration reported correlations between the arrival directions of UHECRs with energies above 57 EeV and positions of nearby AGN [22]. The probability that the correlations for angular separations less than 3.1° has occurred by chance is 1.7×10^{-3}. However, the HiRes group reported that no correlations have been found [23]. To test AGN hypothesis, we use nearby AGN from Véron 2006 catalog [24], with the cut on redshift $0 < z \leq 0.018$. As is seen from Fig. 13 [20], the preliminary TA result is compatible both with isotropic distribution and the AGN hypothesis.

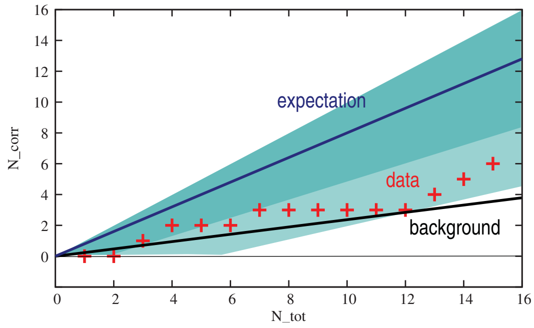

Fig. 13. The preliminary result of the correlations with AGN. The horizontal axis is the number of observed events and the vertical axis is the number of correlated events with AGN. The red crosses are the TA data. The turquoise shaded area shows 1σ region and the light-blue shaded area shows 2σ region. The black solid line is the prediction from isotropic distribution and the blue solid line is the prediction from the result of the Pierre Auger Observatory [22].

Small-scale anisotropy

The small-scale clusters of UHECR arrival directions were observed by the AGASA experiment at the angular scale of 2.5° [25, 26]. On the other hand, the result of small-scale anisotropy by the HiRes experiment is consistent with an isotropic distribution [27]. Following the analysis of the AGASA, we used the events with energies above 10 EeV and 40 EeV. Fig. 14 shows the distribution of separation angles for any two cosmic rays with energies above 40 EeV normalized by solid angle. Then we count the number of pairs separated by less than 2.5°. For the events with energies above 10 EeV, we find 311 pairs while 323 are expected for the isotropic model. For the events with energies above 40 EeV, we find one pair while 0.8 are expected for the isotropic model. No significant autocorrelations (clustering) at small scales were found in the data sets [20, 28].

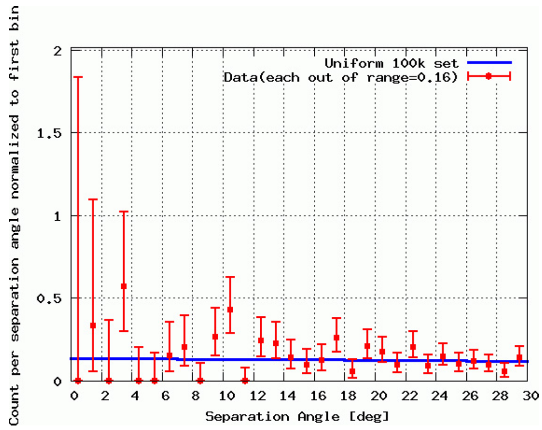

Fig. 14. The preliminary distribution of separation angles for any two cosmic rays with energies above 40 EeV normalized by solid angle. The points are the observed data and the blue line is the isotropic model. Error bars represent the Poisson upper and lower limits at 68% C.L.

Prospects

We will analyze the increasing TA data and measure energy spectrum, particle composition including UHE photons and UHE neutrinos, anisotropy of arrival directions more in detail and explore the origin of UHE cosmic rays and understand the extreme phenomena of the universe by using the characteristic features of the TA detector, the sampling of electromagnetic shower energy, the unique calibration of fluorescence generation, usage of HiRes-1 telescopes in the TA site, and the measurement in the northern hemisphere.

In the near future, we plan to determine energies of air showers within total uncertainty of about 10% and measure the spectrum of UHE cosmic rays precisely by using end-to-end absolute energy calibration of fluorescence telescopes with the ELS.

Towards large-scale UHECR observatory, wide attention has been raised to the detection of UHECR with radio techniques, either passive and active, in addtion to the extention with the surface detectors and/or fluorescence detectors. An R/D study of the detection of radar echoes from extensive air showers (EAS) has started by installing a transmitter and receivers at the TA site. The R/D studies of the detection of bremsstrahlung from EAS are being discussed first by using the ELS.

A construction of TALE, a Low Energy extension of TA with the energy range down to 10^{17} eV is proposed to investigate the modulation of cosmic ray composition and spectrum expected by the galactic to extra-galactic transition of cosmic ray origins including "second knee" in the 10^{17} eV decade. By the TA+TALE project, comprehensive studies on UHE cosmic rays will be possible for wide energy range from $10^{16.5}$ to 10^{20} eV or above.

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