論文内容の要旨

論文題目: テレスコープアレイ地表検出器による
極限エネルギー宇宙線スペクトルの測定
(The mesurement of extremely high energy cosmic ray energy spectrum
by Telescope Array surface detector)
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Introduction

Telescope Array (TA) is a detector for Extremely High Energy Cosmic Rays (EHECRs) constructed in the west desert of Utah, USA. It is a hybrid detector consisting of an air shower array and air fluorescence telescopes (see Fig.1(left)). The air shower array uses 507 surface detectors (SDs) deployed in a grid of 1.2 km spacing, covering the ground area of $\sim$700 km^2. The fluorescence telescopes consists of 38 fluorescence detectors (FDs) distributed over 3 stations surrounding the array.

The measured energy spectrum of EHECR is different in the AGASA experiment and the HiRes experiment, i.e., the AGASA's spectrum is extended toward higher energies without indicating the flux suppression, whereas the HiRes's spectrum demonstrates a cutoff structure at $\sim 10^{19.7}$ eV which can be explained by the Greisen-Zatsepin-Kuzmin (GZK) effect: an energy loss of UHECRs caused by the interaction with cosmic microwave background (CMB). The Pierre Auger Observatory (Auger) recently reported a strong flux suppression as well. The spectra of AGASA, HiRes and Auger were obtained by different detector techniques, i.e., a plastic scintillator array for AGASA, air fluorescence telescopes for HiRes, and a water tank array for Auger.

The TA's SD (TASD) uses the plastic scintillator for particle detection same as AGASA. Two layers of scintillators (thickness, 1.2 cm; surface area, 3 m^2) are used for TASD, and a single layer (thickness, 5cm; area, $2m^2$) is used for AGASA. The TASD covers the ground area of 680 km^2 (altitude, 1380m; latitude, 39.3 degrees North) with 1.2 km spacing, whereas the AGASA's SD covers the 100 km^2 (altitude, 900m; latitude, 35.8 degrees North) with $\sim$1.0 km spacing. For the AGASA, the scintillation light was directly detected by the photomultiplier tube (PMT) and its integrated pulse height and the leading edge timing were read out. For the TASD, the scintillation light was detected by the PMT via wavelength shifting fiber, and the complete waveforms were recorded by the flash ADC (FADC).

The subject of this thesis is to measure the energy spectrum of UHECRs via TASD with more detailed information, higher statistics, and better calibration than the AGASA had done. We also developed an independent data analysis method for the TASD with a help of intense Monte Carlo (MC) simulation of the air shower event.

TASD array

One of the deployed TASD in the field is shown in Fig.1(right). We developed an electronics which enabled a local recording of the waveform (FADC) and the time (GPS) of the SD generated by the air shower events. It also recorded and histogrammed the pulse heights for all the penetrating cosmic rays (CRs), mostly muons, at the rate of $\sim$750 Hz. All the SDs were equipped with this electronics and were operated standalone in the field via solar power system. The trigger and data acquisition was performed using a wireless communication system (IEEE802.11). The CR histogram was read out every 10 minutes, and it was used as a precise real-time calibration in the data analysis. The construction of the TASD was completed in March 2008, and the observation started in May 2008 after 2 months of commissioning.

We reconstructed the energy and the arrival direction of air showers by fitting the observed pattern of SD hit timings and deposited energies with an expectation obtained from the air shower and the detector response simulation programs (COSMOS and GEANT4). The expected distribution was formulated as an air shower model function, which gives the average and the width of individual SD hits depending on the energy and arrival direction of primary CRs, and the information of the SD locations with respect to the shower axis, i.e., the impact parameter and the rotational angle. This method of reconstruction allowed us to determine the zenith angle attenuation of expected energy deposit without using a traditional constant intensity cut (CIC) method. The CIC, which was used for the AGASA data analysis, is based on the assumption that the zenith angle attenuation of the SD energy deposit stays constant with the primary CR energy, which is not supported by the results of our simulation.

Data analysis

We analyzed a total of 393,509 TASD events collected from May 2008 to September 2010 using our reconstruction program. Following cuts are applied to select events used for the spectrum measurement.

- 5 or more than 5 adjacent SD hits with energy deposition > 0.4MeV are required for good reconstruction (145,243 events left).
- 4 or more than 4 good SD (141,857 events left).
- 4 or more than 4 good SD hits with energy deposition > 2.4MeV (93,572 events left).
- Events were passed for the reconstruction program (93,566 events reconstructed).
- 4 or more than 4 good SD hits with energy deposition > 2.4MeV (93,572 events left).
- 4 or more than 4 good SD hits between 500m and 3000m from core position and slower than light speed (59,159 events left).
- The distance from the reconstructed shower core position to the boarder of the SD array is larger than 1.2 km (48,289 events left).
- Reconstructed zenith angle is smaller than 45 degrees (39,305 events left).
- Reconstructed primary energy is larger than $10^{18.8}$eV (2,032 events left).
- χ^2/DoF for the lateral distribution of energy deposit is less than 3 (2,019 events left).
- χ^2/DoF for the timing distribution of shower front is less than 10 (2,011 events left).

To evaluate reconstruction efficiency and energy resolution, we generated simulated events and reconstructed them. The simulated events were generated implementing the real detector conditions such as the calibrations, dead time, and offline (turned off) SDs. They were generated at fixed energies between $10^{18.0}$ and $10^{20.0}$ eV and with uniform arrival directions. The exposure of the measurement was calculated by processing the simulated events in the same manner as the data. As seen in Fig.2 (left), the exposure above 10^{19}eV is nearly constant. The value of $\sim$5.3x10^{16} [m^2 s sr] is approximately the same as that obtained by AGASA for 13 years.

The energy resolution was estimated using the simulated event: it is 17% at 10^{19} eV and 12% at 10^{20} eV (see Fig.2(right)). A systematic shift of up to 10% was observed in the reconstructed energy of MC events, and the same amount was corrected for the reconstructed energy of the observed event. The systematic uncertainty of the energy scale is estimated to be +9%, -13% at 10^{19} eV and +17%, -30% at 10^{20} eV. The largest contribution comes from the unknown primary composition of the UHECRs (proton or iron).

Results and discussion

The obtained energy spectrum is shown in Fig.3(left) after a small smearing effect by the energy resolution is corrected. It is also plotted in Figure 4 (left) together with the data from other experiments. The same set of data is plotted in Figure 4 (right) with energy scales of each experiment adjusted by a constant amount: -5% (AGASA), +16% (HiRes), and +34% (Auger). Theses energy scales are calculated from average flux between $10^{18.8}$eV and $10^{19.2}$eV to agree for all experiments. As seen in Figure 4(right), the observed spectrum by TASD is consistent with existing measurements in the energy range between 10^{18} eV-$10^{19.8}$ eV.

To evaluate the structure of the observed energy spectrum, we fitted the spectrum by double power law model and triple power law model. The result is shown in Fig.3 (left). The parameters obtained by the fit are listed in Table-1.

The observed second breakpoint energy E_2 is $10^{19.72}$eV for the triple power law model. We observed 18 events above $10^{19.72}$eV whereas the expected number of events is 48.5 for the triple power law model (shown in dashed line in Fig.3), and is 36.1 for the double power law model. The probability to observe 18 events or less when 36.1 (48.5) events are expected is 6.8×10^{-4} (4.7×10^{-7}), or 3.2 (4.9) sigma.

The obtained energy spectrum of TASD is compared with the theoretical expectation. We calculated the expected energy spectrum assuming that the CR acceleration sources are distributed uniformly in the extragalactic space, and the protons originating from the source propagate to the Earth rectilinearly experiencing the interaction with the CMB. The calculated spectrum is plotted in Figure 3 (right) in solid green curve. The fit to the observed spectrum was made by the constraint that the integral flux for energies over $10^{18.8}$eV is the same for the data and the expected spectrum, and by optimizing the power law index of CR generation at the source. The best fit was obtained at $\gamma = 2.65 \pm 0.05$ with χ^2/DoF=16.6/13. It is noted that the observed cutoff energy ($E_{1/2}$=$10^{19.70^{+0.05}_{-0.08}}$eV) agrees well with the expectation ($10^{19.72}$eV) for the proton spectrum. For the case of iron acceleration at the source, acceptable fits were obtained only by excluding the data below 10^{19} eV, and by assuming unexpectedly hard spectrum ($\gamma = 2.1$) at the source.

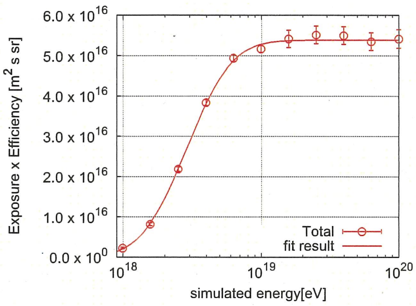
Conclusion

We measured the energy spectrum of UHECRs using the air shower array of TA for energies above $10^{18.8}$ eV. The extended spectrum of AGASA (without cutoff) was dismissed at the CL level of 3.2 sigma or larger. The observed spectrum is well represented by the expected spectrum for the extra-galactic proton experiencing the interaction with the CMB during its propagation to the Earth.

	E_1[eV]	E_2[eV]	γ_1	γ_2	γ_3	$E_{1/2}$[eV]
TASD double	$10^{19.04\pm0.14}$		3.24±0.31	2.83±0.10		
TASD triple	$10^{19.05\pm0.06}$	$10^{19.74\pm0.10}$	3.26±0.14	2.70±0.10	4.9±1.5	$10^{19.72\pm0.06}$
AGASA double	$10^{19.01}$		3.16	$2.78^{+0.25}_{-0.33}$		
HiRes triple	$10^{18.75\pm0.05}$	$10^{19.75\pm0.04}$	3.25±0.01	2.81±0.03	5.1±0.7	$10^{19.73\pm0.07}$
Auger triple	$10^{18.61\pm0.01}$	$10^{19.46\pm0.03}$	3.26±0.04	2.59±0.02	4.3±0.2	$10^{19.61\pm0.03}$

Table 1: Fitted parameters with double/triple power law to TASD, AGASA, HiRes and Auger spectra.

Figure 1: TA detector arrangement (left). black boxes, green boxes, orange circles, blue cross and black arrows represent SDs, FDs, communication towers for SD, central laser facility for FD calibration and FD field of view, respectively. SD and a communication tower (right).



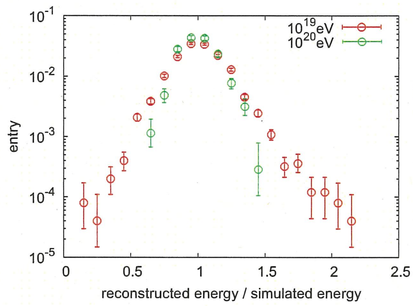
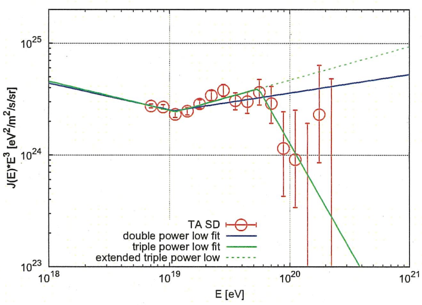


Figure 2: Exposure including total efficiency and utilization ratio (left). Red continuous is fit result. Energy resolution of reconstruction (right). Red circles are for 10^{19}eV and green circles are for 10^{20}eV. Vertical axis is normalized by total number of simulated events.



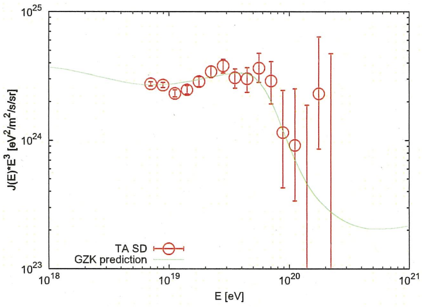
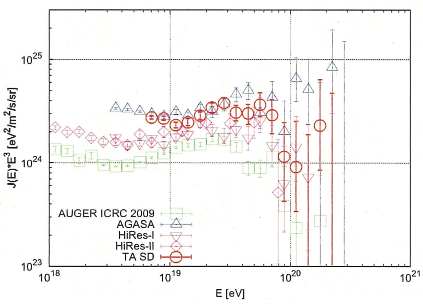


Figure 3: Fit results of energy spectrum (left) by TASD (red circles) using double power law model (blue continuous) and triple power law model (green continuous). Green dashed line is the extension of the middle term of triple power low model. Fit result of energy spectrum (right) by TASD (red circles) using proton spectrum (green continuous),



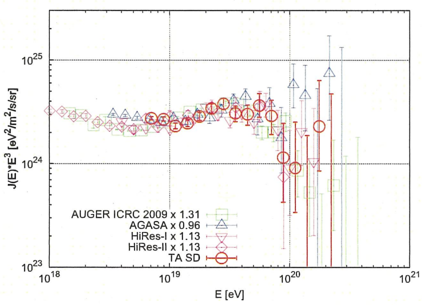


Figure 4: EHECR energy spectra (left) by TASD (red), AGASA (blue) , HiRes-I, HiRes-II (purple) and Auger (green). The error bars in bins of absent event indicate 90% confidence interval for AGASA, and indicate 68% confidence interval for the others. Right figure is same as left, but energy is scaled -5%, 13% and 31% for AGASA, HiRes and Auger, respectively.