論文内容の要旨

Hybrid analysis of ultra-high energy cosmic rays observed with the Telescope Array
(テレスコープアレイで観測した超高エネルギー宇宙線のハイブリッド解析による研究)

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In this thesis, the energy spectrum of UHECRs ($E > 10^{18.7}$eV) was measured using the hybrid data from the Telescope Array. For the precise measurement, the analysis method with the hybrid technique was developed.

The Telescope Array (TA) experiment which is located in Utah desert in United States (39.30 Latitude, -112.91 Longitude and 1382m A.S.L.) is the largest stereo-hybrid detector for UHECR observation in the northern hemisphere[1]. The main target of this experiment is precise measurement of the energy spectrum, arrival direction and composition of UHECR through the investigation of the inconsistency about GZK cut off between the results of the AGASA[2] and HiRes[3]. For this subject, the TA uses the hybrid technique with three stations of Fluorescence Detectors (FDs) which are the same as HiRes technique and 507 Surface Detectors (SDs) which are the same as AGASA technique. Each detector measures UHECRs through the observation of the air showers created by the interaction between UHECRs and atmospheric molecules. SD directly observes particles in air shower on the ground and the FD detects fluorescence photons generated by air showers. Since one of the FD stations, which is the northern station called the Middle Drum (MD), is the detector transferred from the HiRes experiment, we can compare the result from the MD site with the Hires result directly.

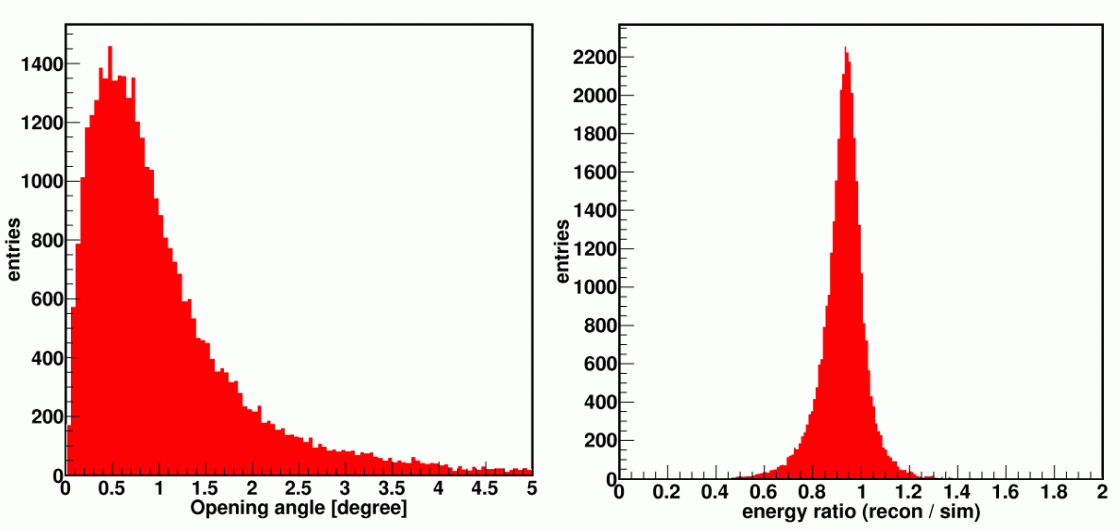

Fig.1. Angular difference between the reconstructed and true arrival directions (left figure) and the ratio of the reconstructed energy to true energy (right figure) for the primary cosmic rays in the MC data. Here we generated MC data with E^{-3} above $10^{18.7}$eV. In the left figure, the peak value is 0.7 degrees and the resolution (68%) is 1.1 degrees. In the right figure, the standard deviation of the energy resolution is 8%.

The ``hybrid'' observation started from March 2008. In this analysis, the hybrid events which are observed both by FD and SD are used to measure the energy spectrum with the developed hybrid reconstruction technique. To carry out this study, the method of the hybrid analysis, in which the timing of SD data is applied to FD monocular reconstruction, is developed. A full hybrid Monte Carlo (MC) simulation with an air shower simulation is developed. The MC simulation includes the Utah atmosphere and the detector response with the time dependence.

The resolutions which are estimated by using the MC simulation are less than 1.1 degrees of the arrival direction and less than 8% of the energy for the observed UHECRs with energies above $10^{18.7}$eV, respectively (see Fig.1). This resolution is quite better than that of the FD monocular analysis. The aperture of the hybrid event is also obtained by using MC simulation.

The used term of the data is from May 27, 2008 to September 28, 2009. The exposure is about 3×10^{15} m2 sr s for at the energy of 10^{19}eV, which is equivalent to 6% of the AGASA exposure. About 2000 hybrid events are found with one FD station (monocular-hybrid events) and about 200 events hybrid events with two FD stations (stereo-hybrid events).

In this hybrid analysis, the main contributions to the systematic uncertainty of energy and flux measurements are the PMT calibration (8%), mirror reflectance (5%), atmospheric attenuation (11%), fluorescence yield (12%). The total systematic error of the energy measurement is estimated to be 19% by a quadratic sum of these factors. The total systematic uncertainty of the flux is estimated to be 12% by the cloud.

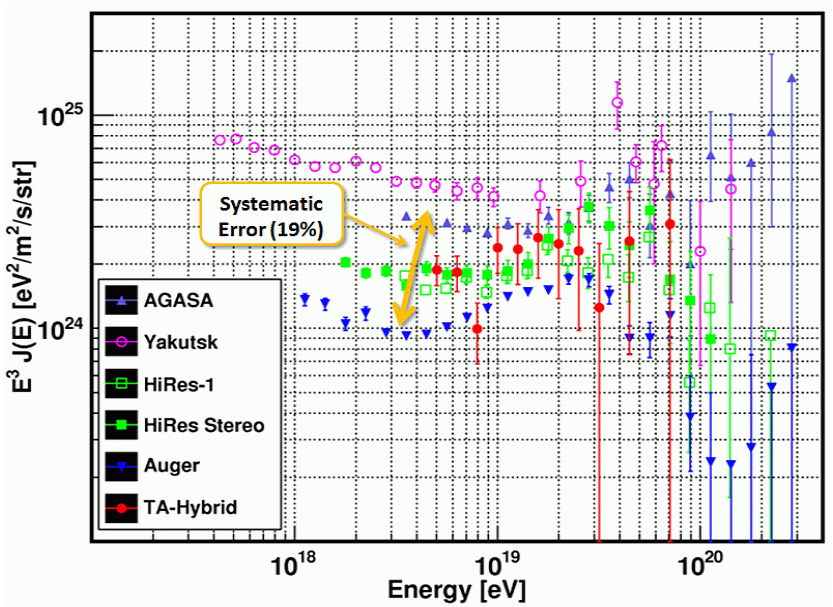

Fig.2. The cosmic ray flux multiplied by a factor of E3 for each bin by this analysis together with the previously published results by other experiments. The horizontal axis is the energy of the primary cosmic ray and vertical axis is the flux J(E)×E3. The red filled circles represent the result of this analysis. The purple filled triangle represent the result by AGASA[2]. The light red opened circles represent result by Yakutsk[4]. The light green open squares represent the result by HiRes-1[2]. The light filled squares represent the result by HiRes Stereo[3]. The blue filled triangles represent the result by Auger[5].

The measured energy spectrum with the developed hybrid technique with energies above $10^{18.7}$eV is shown in Fig.2. It is consistent with the result of HiRes within the total systematic uncertainty.

By the March of 2011, the systematic uncertainty of the energy will be improved to around 10% level by the absolute calibration with a linear accelerator called Electron Light Source (ELS) and the data selection of the good weather. By the improvement of the SD analysis, the energy scale between FD and SD will be compared by the hybrid analysis as the direct comparison between the AGASA and HiRes results. This work will become the verification of the inconsistency of the result of the GZK cut off. In March of 2011, the exposure of the TA will reach about twice of the AGASA total exposure. The TA will measure the energy spectrum around the GZK cut off with the energy uncertainty of 10% level by the hybrid technique and ELS calibration.

[1]http://www.telescopearray.org/

[2]M.Takeda et al., Phys.Rev.Lett.81, 1163 (1998)

[3]R.Abbasi et al., Phys.Rev.Lett.100, 101101 (2008)

[4]V.P.Egorova et al., Nucl.Phys.B 136, 3 (2008)

[5]J.Abraham et al., Proceedings of the 31th ICRC