Future plans for the Telescope Array experiment

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Abstract. The Telescope Array (TA) experiment is the world's first and the only air shower detector to be directly calibrated by an on-site accelerator beam. For wider and deeper understanding of cosmic rays via high precision measurements, we have several future plans for the TA experiment. The first extension plan is an on-going project, called as TA low energy extension (TALE), to extend the sensitive energy range to $10^{16.5}$ eV in order to study the second knee, the predicted galactic-extragalactic transition of dominant sources and air shower phenomena comparing with LHC measurements. The second proposition is exchanges of FDs and SDs between TA and Pierre Auger Observatory, toward understanding systematic uncertainties of these experiments and to solve discrepancies in energy scales and $X_{\rm max}$. The third plan is a huge air shower array, "the world observatory", consisting of a huge number of SDs and/or FDs for the world's largest exposure and the finest accuracy to open a new window on astronomy with ultra high energy particles.

1 Introduction

The Telescope Array (TA) experiment has been used for measuring extensive air showers (EASs) in order to study the origin of ultra-high-energy cosmic rays (UHECRs)[1]. The site is located in the desert of Millard county, Utah, USA (39.3°N, 112.9°W). TA consists of two types of detectors: 507 surface detectors (SDs) arrayed with a spacing of 1.2 km between each SD in an area of approximately 680 km^2, and air fluorescence detectors (FDs) in three stations located around the SDs facing inward and looking over the array. The full operation of the detectors have been started in March 2008.

In the TA experiment we have the most valuable calibration facility which is a electron linear accelerator, called "Electron Light Source (ELS)"[2]. ELS installed 100 m away from the south-east FD station (called BRM station) shoots calibrated electron beams for FDs. The typical energy per electron and the number of electrons are 40 MeV and 10^9, respectively. With this equipment we will achieve an end to end calibration for FDs.

After four years of very stable operations, we have successfully released our results in this conference, although some of these are still preliminary. The results are briefly summarized as follows: The energy spectrum has a clear "ankle" at $10^{18.7}$ eV and a sharp cutoff above $10^{19.7}$ eV. The flux is consistent with the HiRes result. The shape of the spectrum curve, it means spectral indexes and break points on the curve, are fitted to the spectrum curves by HiRes and that by Auger, However, to fit our curve with that by Auger we need to shift primary energies about 20 %. Our preliminary results of mass composition analyses, which are averaged $X_{\rm max}$ and their distributions, show that protons dominate the primary composition of observed showers. This preliminary conclusion contradicts the Auger's results[3], which show a transition of the dominant composition from light to heavy, derived from averaged $X_{\rm max}$ values and their distributions. From arrival direction distribution analyses, we do not observe the departure from isotropic, but the arrival direction distributions are also compatible with the large scale structure of the matter distribution.

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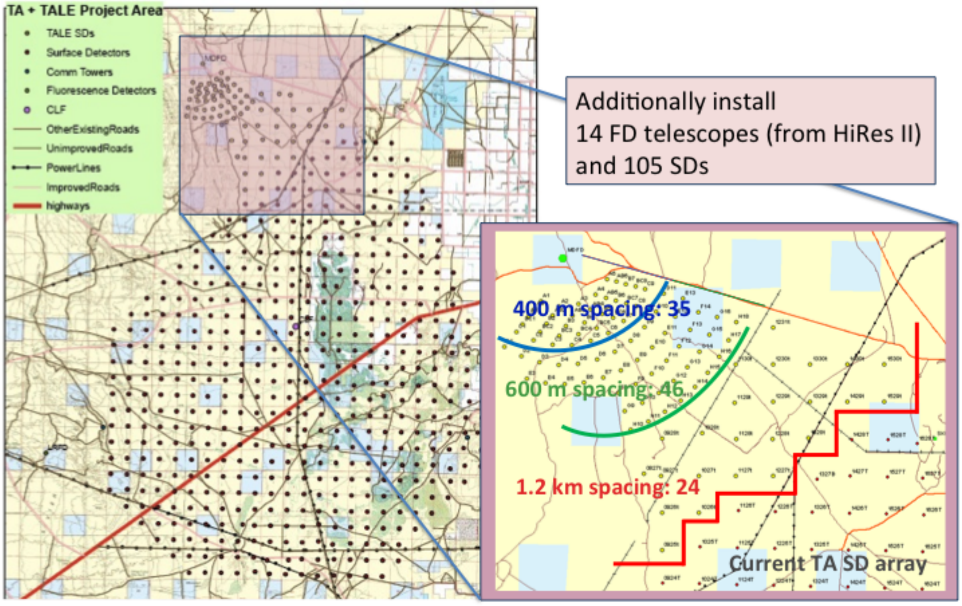

Fig. 1. (*left*) The overall view of the TA SD array and the planed the TALE array. TALE is installed on the north-west boundary of the TA SD array. (*right*)The planed locations of the TALE SDs. The SD density increases toward the Middle Drum FD station.

2 TA Low energy Extension (TALE)

The first future plan, actually which is on-going project, is an extension of our observation efficiencies for primary energy measurements and for primary composition measurements to low energies. It is called TALE, which stands for TA Low energy Extension. The aim of this project is to search for the galactic to extra-galactic transition of the dominant cosmic ray source population, to study iron-knee which reported by HiRes-MIA experiment[4], to measure 2nd knee of energy spectra which measured at $10^{17.5}$ eV by several experiments, and to confirm air shower models using hybrid techniques and calibrations by ELS, including and comparing with results from by LHCf and other accelerator experiments.

In the current plan, TALE is the additional installations of 14 FD telescopes transfered from HiRes II and 105 SDs. These components will be installed at one of TA FD stations, which is called Middle Drum (MD) station, where the HiRes I telescopes are working as a part of the TA FD system. The additional surface detectors will be deployed between the MD station and the north-west border of the TA SD array, as shown in Fig. 1. The detector density is not constant but rather increasing toward the MD station, which means that 24 SDs will be deployed with 1.2 km spacing bordered on the TA SD array, and 46 SDs will be deployed with 600 m spacing, and near the MD station the detector density reaches 400 m spacing for 35 SDs. This gradual density increase provides a good hybrid efficiency for wide energy range.

TALE FDs make the two ring configuration of the field of view to observe air showers at elevation angles from $31° - 59°$, in addition to the current Middle Drum fluorescence telescopes observing from $3° - 31°$ in elevation. The TALE FD's shed has been constructed just beside the Middle Drum station. On the other hand, the production of SDs have also started recently. The design of SD is identical with the detector used in the TA SD array.

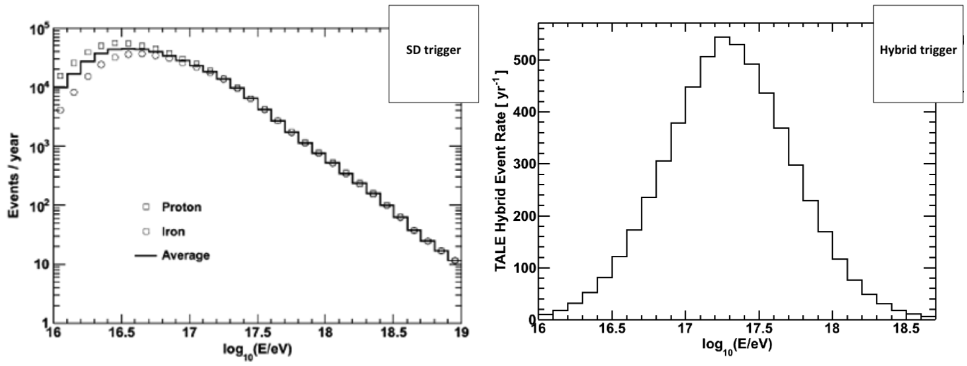

Fig. 2. (*left*) An expected number of TALE SD triggers per year. The plots show MC results for primary protons and for primary irons, and the line is the average of the plots at each energy bin. (*right*)An expected number of hybrid triggers per year.

The expected number of events by the TALE SD array is 50,000 with the mode energy of $10^{16.5}$ eV, and for hybrid events the expected event rate is 5,000 per year with the mode energy of $10^{17.3}$ eV. The expected energy distributions are shown in Fig. 2.

3 Exchange of FDs and SDs between TA and Auger

As many reports and discussions have been shown in this symposium, the TA's preliminary results and the results reported by Auger have serious discrepancies in the energy scale and in longitudinal development measurements, such as averaged $X_{\max}$ and $X_{\max}$ distributions. The working groups were organized and will continue to make effort to solve these problems. For example, exchanging data or exchanging calibration devices will be discussed, but I would like to propose exchange of experimental equipment between TA and Auger. The minimum requirement for this plan is an exchange of two TA's FD telescopes with one Auger's FD telescope. It is equivalent to the exchange of 20° – 30° FOVs, and its cost can be estimated very roughly at about one million dollars. On larger scale, if we can exchange one FD station plus 100 SDs with each other, it will provide valuable results to solve various problems, and it will enhance our knowledge about air shower phenomena. The estimated cost is about ten million dollars.

4 A huge air shower array as the world observatory

With the previous future plan, exchange of equipment, must solve the discrepancies between TA and Auger in the near future. As a result, if we recognize the TA's preliminary results, these suggests that, for the energy spectrum there is a sharp cutoff at the highest energy end, and for the mass composition primaries are purely protons above 10^{18} eV. These results are consistent with the GZK mechanism on primary protons. Then remaining biggest question is origins of UHECRs, which means source objects, injection and acceleration mechanisms, and their propagations.

A particularly good strategy for searching point sources is to concentrate on observations of UHECRs in the highest energies. This restriction of the energy range brings in a limitation of the number of sources which contribute to the observed events, and as a result it provides easy source identifications.

If we assume primary protons, the mean free path of the cosmic rays decreases with increasing energies with the GZK mechanism. Thus, the volume of the GZK sphere and then the number of sources also decrease with increasing energies. For example, based on the mean free path calculated by Takami et al.[5] with assuming the source density is 10^{-4} Mpc^{-3}, at $E = 10^{19.6}$ eV, the GZK sphere radius, R_{GZK}, is about 200 Mpc and the number of sources, N_S, is about 4000. At $E = 10^{19.8}$

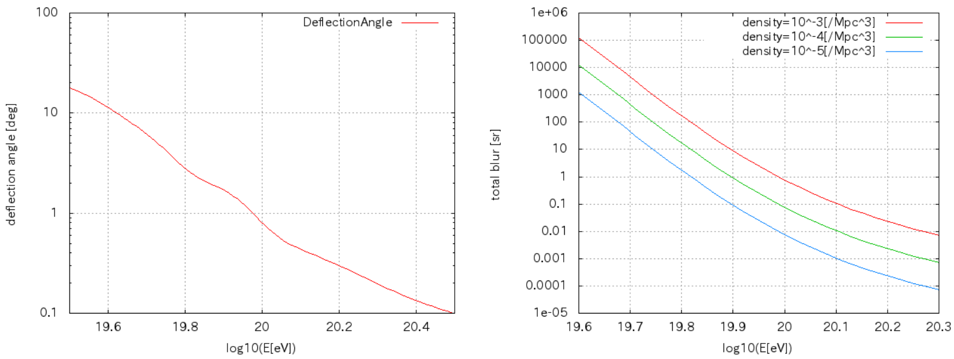

Fig. 3. (*left*) The blur, *i.e.*, the RMS of deflection angles, calculated with a formula used by Auger group[6]. In this calculation, the galactic magnetic field strength is taken into account. (*right*) The product of the number of sources and the solid angle of the source resolutions. At the energies for the products $< 4\,\pi$ UHECR sources can be resolved as point sources.

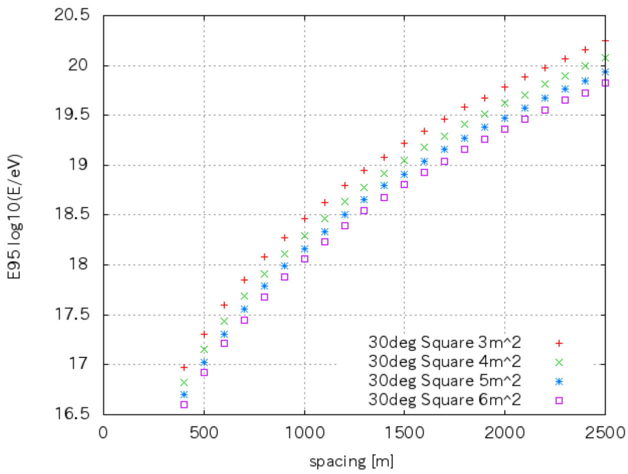

Fig. 4. The vertical axis shows threshold energy, E95, of air shower arrays. The threshold energy is defined as the triggering efficiency is 95 % at E95. The horizontal axis shows array spacing distances. Theses relations were calculated with very simple MC calculations based on empirically modified Gaisser-Hillas function and empirically modified NKG function.

eV, $R_{GZK} \sim 60$ Mpc and $N_S \sim 100$. At higher energy, for example at $E = 10^{20.0}$ eV, the number of contributing sources is reduced to 10 with $R_{GZK} \sim 30$ Mpc.

To enable us to resolve sources on the sky map the product of the number of sources and the solid angle of a resolution is needed to be less than $4\,\pi$ steradians. The source resolutions depend on blurs, RMS of cosmic ray's deflection angles by magnetic fields, and detector's angular resolutions. The RMS of deflection angles calculated with a formula used by Auger group[6] is shown in Fig. 3(*left*). On the other hand, here we assume the detector's angular resolution of 2.1°, which is slightly larger than the TA SD array's resolution. As a result, the product of the number of sources and the solid angle of the source resolution is obtained as shown in Fig. 3(*right*) for the several source density assumptions. Setting the upper limit of $4\,\pi$, the target threshold energy is determined to $10^{19.8}$ eV.

Once we determined the threshold energy, we obtain an optimum value for the detector spacing. Assuming the square grid alignment of the current TA SD, which has the sensitive area of 3 m^2, a simple Monte Carlo calculation, shows the optimum spacing is 2.0 km, and this spacing gives 95 % detection efficiency at $10^{19.8}$ eV, as shown in Fig. 4.

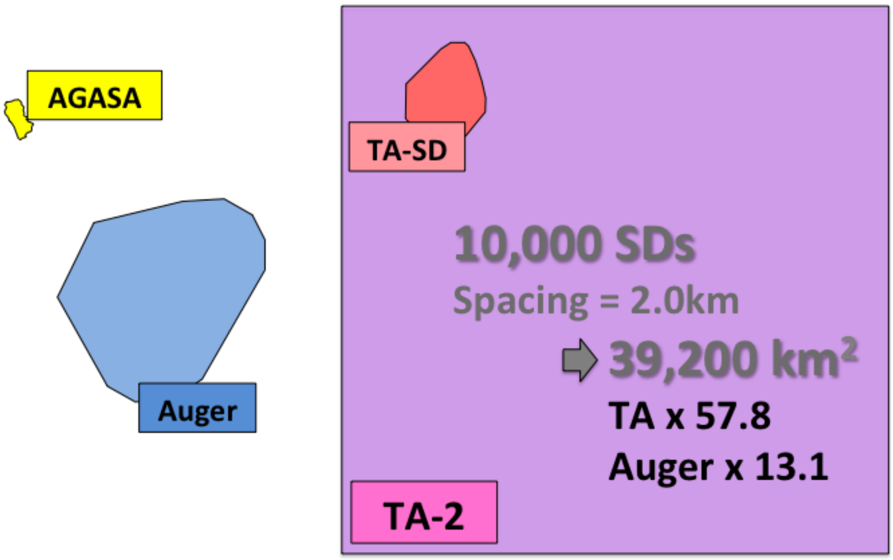

Fig. 5. Comparison of the coverage area of the proposed huge array, tentatively called "TA-2" here, with the others.

Here I would like to propose a huge air shower array to target highest energy cosmic rays with this optimum spacing. For example, if we prepare 10,000 TA SDs deployed with 2.0 km spacing, the array coverage reaches 39,200 km^2. Compared with the current experiments, this size is 58 times bigger than the TA SD array and 13 times bigger than the Auger SD array(see Fig. 5). Assuming the measured energy spectrum by TA, the expected number of events is calculated, and it is 430 events per year above 57 EeV, and it is 26 events per year above 100 EeV. With this large statistics at the highest energy region, even if a smearing angle for UHECR's arrival directions of 20°, the isotropic model and anisotropy along with the large scale structure can be discriminated with more than 95 % CL with one year observations [7].

Takami and Sato[8] claimed that a high statistic is essentially important for source identifications. They mentioned that 2500 and 250 event detections above $10^{19.8}$ eV can unveil their source distribution for the source number densities of 10^{-4} and 10^{-5} Mpc^{-3}, respectively. The proposed huge air shower array achieve this level of statistics less than ten years. Event if the actual source density is higher than the assumption in their discussion, setting the threshold energy to higher provides strong correlations between UHECR events and selected nearby sources. Moreover, if the deflections by galactic and extra-galactic magnetic fields are larger than an expectation, energy-position correlated multiplet analysis tried by Auger group[6] is helpful for source identification. Thus, the good energy and angular resolutions are essentially important.

The total construction cost for this huge array of 10,000 SDs is 100 million dollars, if we assume the unit price for one SD is 10,000 dollars. It is 90 % of the TA SD's unit price including the deployment costs. If we obtain the full budget for the project in 2015, which is very optimistic case, we will spend seven years for staking, SD productions and deployments, and then the full operation will start at the end of 2021.

5 Conclusions

Here we introduce three future plans of the Telescope Array. The plan firstly mentioned is called TALE, and it is a on-going project. A part of the system will start operations in early 2013.

The third plan is a huge air shower array. The key feature of this idea is to concentrate its sensitivity on the highest energy range and to achieve a huge coverage reaching to 40,000 km^2. We need further studies about, for example, the optimum size of the experiment, array configurations, detector types, *i.e.*, whether scintillators or water tanks is better, DAQ communication system between detectors, etc. And also we need careful studies and discussions about the importance of the sensitivity for neutrino with this array.

Finally, the plan secondly mentioned, exchange of FDs and SDs, to study systematic differences between TA and Auger with observations and analyses for same showers, same laser beams and same accelerator beams, will provide us solutions for the discrepancies. In addition, this project with enhancement of the cooperative relationship between TA and Auger is a critically important step for further extensions of UHECR researches.

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