The Telescope Array Experiment: An Overview and Physics Aims

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Abstract

The Telescope Array (TA) experiment plans to deploy an array of 10 telescope stations in the west desert of Utah, USA and observes extremely high energy cosmic rays (EHECRs) by the atmospheric fluorescence. Its purpose is to study super-GZK (E $> 10^{20}$ eV) cosmic rays discovered by AGASA. In order to identify the origin of super-GZK events, TA has ∼30 times larger aperture than AGASA and provides a particle identification by the shower profile measurement. The first step of construction will start as a hybrid detector with an AGASA×10 ground array and a part of fluorescence telescopes, which will unambiguously establish

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the existence of super-GZK and cluster events with much improved statistics and systematics. This paper describes the physics of TA and its overall planning.

1. Physics of Telescope Array

The AGASA so far observed 11 super-GZK cosmic rays in 12 years of operation. The energy spectrum continues toward high energy without showing an indication of the GZK-cutoff[1]. The arrival directions are isotropic and does not show a correlation with the galactic plane or the super-galactic plane of nearby galaxies. A few point-like clusters were observed in the sky, from which 2 or more EHECRs were arriving[2]. High energy astronomical objects have been searched behind these events but no apparent candidates were found. A correlation with quasar remnants[3] and the BL Lac objects[4] had been suggested, but none seem definitive at this moment. The latest results of AGAGA are reported elsewhere in this conference. Several hypotheses have been proposed to explain super-GZK events and clusters[5];

- The production of EHECRs by the decay of long-lived, super-heavy relic particles concentrated in the halo of our galaxy and with some level of clumping to produce clustered events.
- The production of Z° by the collision of cosmological neutrino background with extremely high energy neutrinos ($E \geq 10^{21}$ eV) produced deep in the universe. The EHECR is produced as a decay product of Z°. The primordial neutrinos may be concentrated in the local super-cluster of galaxies by its gravitational interaction with the dark matter.
- The Lorentz invariance breaks down at a very high Lorentz factor such that the high interaction cross section of pion photoproduction via $\Delta(1232)$ resonance is avoided.
- The generation of EHECRs by the yet unknown dark stars which are over-populated by a factor of $\sim$10 in the vicinity of our galaxy.

Note that the Z-burst and the violation of Lorentz invariance explain the extension of the spectrum above GZK cutoff, but they leave the question of acceleration itself unanswered. It is certain that super-GZK events and clusters are difficult to explain in the standard framework of astrophysics and particle physics.

2. Prospects

The models with super-heavy relics and the Z-burst have a clear experimental signature to be tested, i.e. EHE gamma rays and neutrinos are an order of magnitude more abundant than protons in these models. The super-heavy relics

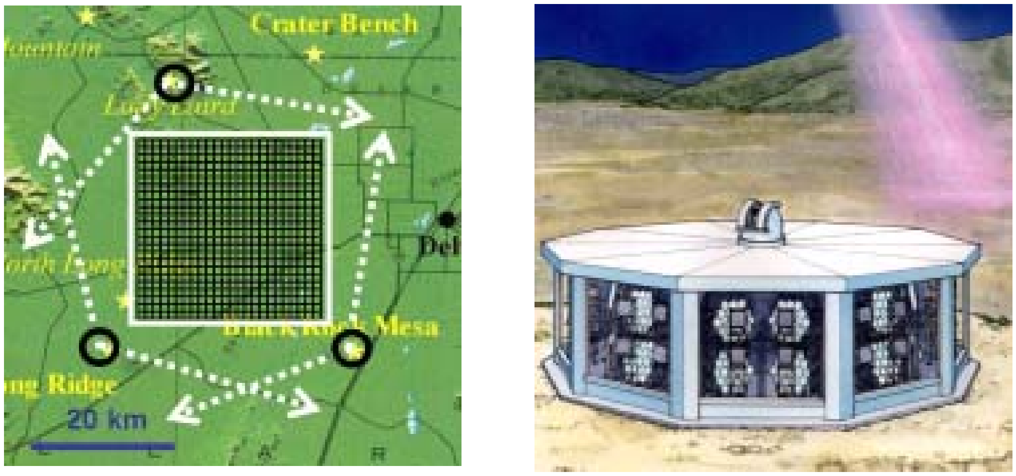

Fig. 1. The Hybrid TA (left panel) is composed of 576 plastic scintillation counters covering the ground area of 760 km^2 and 3 fluorescence telescope stations (right panel) surrounding the ground array and looking inward.

model also expects a concentration of the sources in the center of the galaxy. A realistic test of Lorentz invariance becomes possible when we identify the source objects of EHECR and measure the distance to the source. The detection of heavy nucleus as a major composition of the EHECR, on the other hand, excludes most of the particle physics origin and directly leads us to the shock wave acceleration. Thus, we expect the TA and the other next generation EHECR experiment will give a clear answer to many of these hypotheses.

The experimental situation around the GZK cutoff became unclear when the HiRes group submitted a paper[6] recently on the first measurement of the energy spectrum and concluded that it is consistent with the existence of the GZK cut-off. Discussions after the submission of the paper can be summarized as follows;

- Taking a systematic uncertainty of the energy determination by two groups, 25% for HiRes[6] and 18% for AGASA[7], the claim of neither group on the existence of the GZK cutoff has a statistical significance higher than 3 σ.

- Below 10^{20}eV where the comparison can be made with enough statistics, the energy spectra of both agree perfectly well, if we remake the HiRes spectrum by increasing the energy of all HiRes events by 25%, or by decreasing the AGASA energy by the same amount.

It is clear that the key of resolving the issue is the higher statistics and better understanding of the systematics. This can be best achieved by a large hybrid experiment making a simultaneous measurement with an AGASA type air shower

Table 1. Expected Acceptance, Resolution and Number of Events of Hybrid TA

Detector	Acceptance (km^2 sr)	Angular Resolution	# of Events per Year $E > 10^{19}$ eV	$E > 10^{20}$ eV
AGASA	162	1.6°	100	1
TA:Ground Array	1371	1.0°	700	9
TA:Fluorescence	670	0.6°	300	4
TA:Hybrid	165	0.4°	80	1

array and a HiRes type air fluorescence telescope. The good statistics can be obtained by building a large ground array, which is relatively inexpensive and its stable operation and uniform coverage over the sky have been guaranteed by the experience of AGASA and other arrays. The better understanding of systematics can be made by the fluorescence measurement, which allows us a calorimetric measurement of the shower energy, a direct observation of the arrival direction and a determination of primary particle species by the shower longitudinal profile.

We therefore propose to urgently build a hybrid TA, an AGASA×10 ground array with a set of fluorescence stations making a simultaneous measurement with the ground array (see Figure 1). It will be built in the West desert of Utah, USA, and will become a first step of constructing the full TA[8]. The performance of the hybrid TA detector is summarized in Table 1 and further details are given elsewhere in this conference. The plan is to complete the hybrid TA by the end of 2006. We expect the full sky survey of EHECRs will be started by the southern hemisphere Pierre Auger observatory in Argentina in 2005, and the hybrid TA will start contributing to the northern hemisphere survey in 2007. We hope that astonishing discoveries of AGASA are confirmed, and the origin of super-GZK and cluster is identified by 2010.

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The Telescope Array Experiment: Hybrid Measurement of Ultra High Energy Cosmic Rays in Northern Hemisphere

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Abstract

The result of AGASA shows the extension of the cosmic ray energy spectrum above the GZK cut-off. Several new generation experiments are planned or under construction to identify the origin of such ultra high energy (UHE) cosmic rays exceeding the cut-off. We report here the design of hybrid Telescope Array (TA) and introduce plans of improving the accuracy of measuring the energy spectrum by the hybrid measurement of ground array and air fluorescence telescope.

1. Introduction

The AGASA energy spectrum shows that there is no indication of GZK cut-off expected by the photo-pion production of the ultra high energy cosmic rays. There is also an indication of point sources in the arrival direction of such cosmic rays [1]. If the origin of these cosmic rays is some type of already known astronomical object, it must exist within several tens of Mpc from our galaxy. Until now no astronomical object is identified in the directions of the observed UHE cosmic rays. Several top-down models are proposed as a remedy, in which UHE cosmic rays are produced via anomalous physics processes or by unknown astronomical objects [2]. In order to get a definite answer on the origin of UHE cosmic rays, it is crucially important to measure the energy spectrum, the arrival distribution and the composition more accurately and compare them with the predictions of these models. We therefore proposed the Telescope Array as the next generation air shower experiment [3] and planned to observe air showers by the air fluorescence technique. On the other hand, HiRes group recently reported that there is a GZK cut-off in their observed energy spectrum [4]. It seems clear

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that a part of the inconsistency is due to the systematic error of both experiments in the determination of primary cosmic ray energies [4]. Taking this critical situation into account, we now intend to observe air showers with an AGASA type ground array and with an air fluorescence detector simultaneously as the first step of the TA project. In this paper, we present a simulation study to confirm how much the systematic error is improved in the primary energy estimation by using our hybrid detector.

2. Experimental Plan

Fig. 1. The prototype camera and telescope reflector for the fluorescence measurement.

In our design of the hybrid-TA, an array of 24×24 plastic scintillators covering the ground area of 760 km^2 is surrounded by three air fluorescence stations. The West Desert in Utah, USA is taken as the experimental site. The total field of view of each station is $3° - 34°$ in the elevation angle and 120° in the azimuthal angle, with all of the three stations looking toward the center of the ground array. The separation of the station is $30 - 40$ km and the stereo acceptance is $\sim$670 km^2 sr for UHE cosmic rays falling within 45 km of the station. The fluorescence acceptance alone is 4 times larger than that of AGASA assuming 10% duty factor. Approximately 60% of the events for E $> 10^{20}$ eV is observed by all 3 stations.

The field of view of each telescope is 18.0° in azimuth and 15.5° in elevation. The telescope has a spherical dish of 3.3 m diameter composed of 18 hexagonal segment mirrors (see Fig.1). The focal length is 2960 mm and the spot size on the focal plane is $\sim$30 mm in FWHM according to a ray tracing calculation. The air shower image is recorded by a camera composed of 16×16 2-inch PMTs placed on the imaging plane (see Fig.1). Each PMT pixel covers $1.1°\times1.0°$ patch of the sky. A signal from the PMT is amplified by a factor of 4 with a pre-amplifier and is sent to a Charge Successive Integrators (CSI) circuit. The CSI integrates a signal every 200 ns and send it out successively to a 12-bit pipeline ADC by means of 3 capacitances operated in a rotational sequence. A self-ranging H/L gain scheme is adopted to cover a dynamic range corresponding to $1-64$k photoelectrons. The digitized signal is fed to a Digital Signal Processor (DSP) to search for a fluorescence signal by maximizing the S/N ratio in 25.6 μs time window.

By one year operation of the hybrid-TA, we will collect $\sim$12 events with E $> 10^{20}$ eV and more than 900 events with E $> 10^{19}$ eV, of which $\sim$80 events are measured simultaneously by both the scintillation detector array and the air fluorescence telescopes.

3. Simulation Procedure

The simulation of UHE cosmic rays by the full Monte-Carlo is practically prohibited by the computation time. In our analysis of the hybrid event, we first generate UHE events using a thinning method. The proton is assumed as a primary and the first interaction depths are sampled by the Monte Carlo simulation. The longitudinal development (LD) profiles are calculated analytically with a modified Gaisser-Hillas function, in which 6 parameters characterizing LDs are estimated with empirical formulas. These formulas are derived from the results of a small amount of simulated events with Corsika Monte Carlo package. Fluorescence and Cherenkov photons are generated according to the LD function and the transmission of photons in the atmosphere is simulated taking effects of Rayleigh and Mie scattering into account. For the determination of the primary energy, it is important to estimate the effects of these scatterings accurately. Note that in the event generation we adopted 1.2 km for the aerosol scale height, h, and 20 km for the attenuation length for the Mie scattering. In the final stage of the simulation, PMT output signals are generated by taking optical properties of the telescopes and cameras into account. The produced shower signal was analyzed, and its energy and arrival direction were reconstructed by the χ^2 minimization method. Details of the analysis procedure are described in our design report [3].

4. Method to Improve Systematic Error

Following is one of the ways we are considering to improve the systematic error of the energy determination using the hybrid event. (a) First a primary energy, E, and an air shower size at the array altitude, N_F, are estimated with a corresponding LD profile reconstructed by the air fluorescence measurement. (b) Then the obtained E is corrected by multiplying a factor N_G/N_F, where N_G is the measured shower size by the ground array. In the AGASA experiment, the primary energy is estimated from the observed local particle density at the core distance of 600m. In this procedure, a major part of 18% total systematic error comes from the uncertainty in the adopted Monte Carlo simulation notably from the differences of used hadronic interaction models and the assumed primary composition. On the other hand, the measurement of N_G itself can be as good as 10% or better, and this is used for the correction of E in our method. In the following analysis, we artificially produced $\sim$20% systematic error in the fluorescence energy measurement by reconstructing the LD profile using a“wrong scale height of 2.0 km and 0.4 km against 1.2 km used in the event generation. Whereas the value of N_G at the array altitude is generated by smearing the correct shower size by 10%.

5. Result

The simulation is performed for primary energies of 10^{19}, 10^{20} and 10^{21} eV with zenith angles less than 60° and with impact parameters from the center of the ground array less than 10 km. For each primary energy, 200 events are generated. The result for the events with E = 10^{20} eV is shown in Figure 2. Before the correction, the estimated energies are ∼14% less or ∼21% more than the generated value of 10^{20} eV by adopting the wrong scale height of 0.4 km or 2 km. This is shown in the upper panels of Figure 2. After the correction, the systematic shift of the measured energy is reduced as seen in the lower two panels of the Figure 2. The present results are summarized in Table 1. It is shown that even when there is ∼20% systematic shift in the air fluorescence energy measurement, we can reduce the error within ∼10% by adopting our method with a minor sacrifice in the resolution. Now we are improving our reconstruction program in order to reduce the systematic error even further.

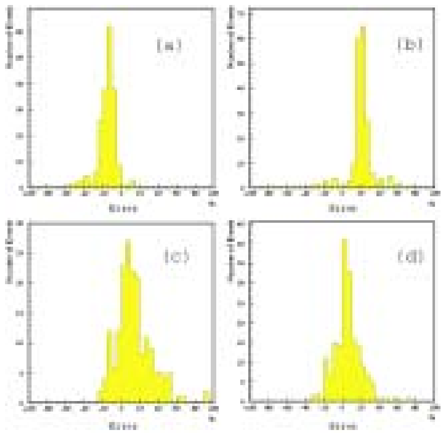

Fig. 2. Distributions of the energy measurement errors for E = 10^{20} eV by using a "wrong scale height of 0.4 km (a and c) and 2 km (b and d).

Table 1. The improvement of the systematic error.

E (eV)	Adopted h (km)	av. E shift ± resol. before correction	av. E shift ± resol. after correction
10^{19}	0.4	$-9.5 \pm 6.0\%$	$+14.9 \pm 16.7\%$
10^{20}	0.4	$-13.9 \pm 6.3\%$	$+10.1 \pm 18.4\%$
10^{21}	0.4	$-17.7 \pm 6.8\%$	$+8.6 \pm 17.1\%$
10^{19}	2.0	$+21.7 \pm 6.0\%$	$-4.1 \pm 12.5\%$
10^{20}	2.0	$+21.2 \pm 4.8\%$	$+4.8 \pm 13.1\%$
10^{21}	2.0	$+21.8 \pm 5.8\%$	$+2.9 \pm 11.7\%$

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The Telescope Array Experiment: The Search for The Clusters in The Northern Hemisphere Sky with A Large Scintillator Array

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Abstract

In addition to the existence of extremely high energy cosmic rays (EHECRs) above GZK cutoff, the results of AGASA shows the clustering of EHECRs above $10^{19.6}$ eV. Confirming such clusters and identifying the corresponding astronomical object is crucial to understand the origin of EHECRs. The northern hemisphere sky is ideal for this purpose since the deflection by the galactic magnetic field is expected to be small and uniform compared to the southern hemisphere. In this paper, we report a design of the large ground array placed at the center of the hybrid-TA experiment. The array has an acceptance 9 times larger than AGASA. Using this detector, the cluster in the northern hemisphere will be searched with an angular resolution better than 1 degree.

1. Introduction

So far AGASA has obtained nice results about the existence of super-GZK particles. The results suggest a uniform distribution in the arrival direction of EHECRs and at the same time the existence of clustering in some directions (see

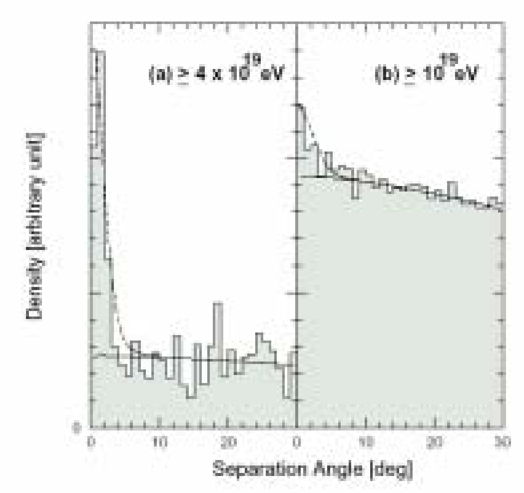

Fig.1 Distribution of spatial angle between two cosmic rays measured by AGASA. All possible combinations are included.

Fig.1). The candidate astronomical objects should have a large enough volume to accelerate the nucleons up to 10^{20}eV or higher, but we so far have not been able to locate any such object within 50 Mpc of the Earth as sources of those EHECRs and clusters. This introduces serious problems to understand the origin and acceleration mechanism of EHECRs.

Several models have been proposed to try to give answer for these issues, such as a decay of super massive relic particles or cosmic strings[1], a breakdown of special relativity at the energy above 10^{20}eV[2] and so on. But none of them seems to be able to convince people. Considering these problems we have keen interest to confirm the existence of super-GZK cosmic rays and especially their clustering.

2. Performance of Hybrid-TA Ground Array

The overall plan of hybrid-TA is presented elsewhere in this conference. One of the major aims of the hybrid-TA is to quickly settle the issues around the clustering of EHECRs with higher statistics. To achieve this target, we have decided to add conventional scintillation detectors as a ground array in addition to the fluorescent detectors originally planned in the TA project. Here we would like to concentrate on presenting the design and the performance of the ground detector array. Total 576 detectors are to be distributed in 24x24 matrix covering the area of 760 km^2 in 1.2 km mesh. Its acceptance is 9 times larger than that of present AGASA. Each detector is a plastic scintillator of 3 m^2 area and 2 cm thickness. The scintillation light is collected to a photomultiplier using wave length shifter bars installed in a groove cut on the surface of the scintillator. We calculated the detection efficiency for the present arrangement; it is around 50% at $10^{18.5}$ eV and becomes full above 10^{19} eV.

The plastic scintillator mainly measures the electrons and positrons in the air shower. It is easier than measuring other components such as muons and hadrons, since the total number of electrons and positrons is roughly 10 times larger and no special preparation is required. Better statistics in terms of the number of charged particles in the detector can be achieved with smaller detector size compared to the water Cherenkov detector. In addition, the measurement of electrons and positrons are less affected by the primary composition and the details of the hadronic interaction at UHE because nearly 90% of the total energy is converted to the electromagnetic component near the shower maximum where the ground detector samples the air shower. This means the plastic scintillator has inherently better energy resolution and less systematic uncertainty compared to other types of particle detectors. It should also be noted that, starting as low as 10^{14} eV, a series of energy spectrum measurements has been made by the plastic scintillator array, including AGASA, and valuable experiences have been accumulated. The continuation and consistency is a good asset for establishing a reliable energy spectrum at extremely high energy.

We adopt two approaches to achieve a good angular resolution with the present ground detector system; One is to obtain a good timing standard for all the 576 counters and another is to obtain a good timing resolution for the hitting time of each counter, which is achieved by recording the time profile of all the charged particles hitting the counter by the flash ADC. As the time standard, we found an accuracy of 20ns can be rather easily achieved with ordinary GPS, and a better time resolution can be expected with the differential GPS system or by some other means such as selecting the same set of satellites for all the counters. These techniques are now being tested. We eventually aim at reaching 10ns accuracy by adopting these methods.

Fig.2 Prototype Flash ADC Board

The Flash ADC board developed for the ground array is shown in Fig.2. It has a 50 MHz 12-bit ADC, a comparator for generating a local trigger, a CPU and a TCP/IP network interface. The connection to the GPS is made by a RS232 serial port. With a conventional fast timing system, one measures the timing of first arriving particle at the front of the shower disk. The arrival direction of the air shower is determined by combining all the timing information and fitting it to the shape of the shower front. In such a case, there can be a large fluctuation in timing measurement, especially where the particle density is sparse, and achieving a good angular resolution is limited. Using the flash ADC system, a complete history of ~10μs after the arrival of the shower front will be recorded with 20ns time resolution. We then can observe the distribution of arriving particles with time and determine the structure of the shower disk. It will give us a great advantage to have better resolution in the angle measurement. We are expecting the accuracy of 1 degree can be achieved with the present FADC system.

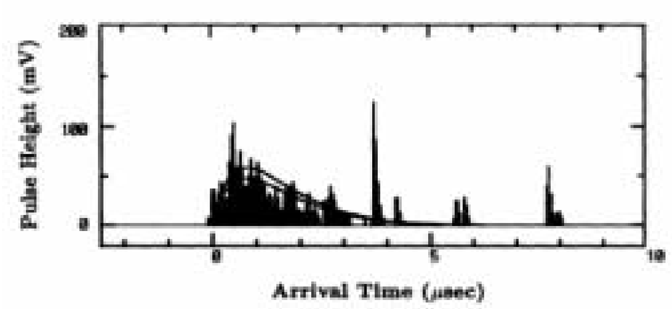

Fig.3 Time profile of 30 m^2 scintillation counter signal observed 2 km away from the shower core of a large air shower event (E=$2x10^{20}$ eV) observed by AGASA.

In terms of the energy resolution of present design, major contribution comes from the fluctuation in the sampling of shower particles. We presently estimate that the error for the determination of primary energy is around 30% at $10^{19.5}$eV and 25% at 10^{20}eV. On the other hand, we expect that the systematic uncertainty of the energy determination will improve because the time structure of the shower disk will be better understood for the new array. An example is shown in Fig.3. This time profile is obtained by a large ($30m^2$) scintillator near the core of AGASA EHECR event. The signals 4,6 and 8 μs after the shower front is considered to be delayed neutrons associated with the shower. In the new flash ADC system, we can explicitly exclude these signals from the energy calculation and improve the systematics, though the energy shift of AGASA arising from these effects is estimated to be only 5%[3].

The whole system will be operated stand alone using a solar panel power generation. Since a large amount of detectors are required, stable and reliable detectors are essential. We believe the present system is robust and easy to deploy and maintain in the desert.

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