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Detection of ultra-high energy cosmic ray showers with a single-pixel fluorescence telescope

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ABSTRACT

We present a concept for large-area, low-cost detection of ultra-high energy cosmic rays (UHECRs) with a Fluorescence detector Array of Single-pixel Telescopes (FAST), addressing the requirements for the next generation of UHECR experiments. In the FAST design, a large field of view is covered by a few pixels at the focal plane of a mirror or Fresnel lens. We report first results of a FAST prototype installed at the Telescope Array site, consisting of a single 200 mm photomultiplier tube at the focal plane of a 1 m^2 Fresnel lens system taken from the prototype of the JEM-EUSO experiment. The FAST prototype took data for 19 nights, demonstrating remarkable operational stability. We detected laser shots at distances of several kilometers as well as 16 highly significant UHECR shower candidates.

1. Introduction

The origin and nature of ultra-high energy cosmic rays is one of the most intriguing mysteries in particle astrophysics [1]. Given their minute flux, less than one per century per square kilometer at the highest energies, a very large area must be instrumented to collect significant statistics. The energy, arrival direction, and mass composition of UHECRs can be inferred from studies of the cascades of secondary particles (Extensive Air Shower, EAS) produced by their interaction with the Earth's atmosphere. Two well-established techniques are used for UHECR detection: (1) arrays of detectors (e.g. plastic scintillators, water-Cherenkov stations) sample EAS particles reaching the ground; (2) large-field-of-view telescopes allow for reconstruction of the shower development in the atmosphere by imaging UV fluorescence light from atmospheric nitrogen excited by EAS particles.

The Pierre Auger Observatory (Auger) [2,3], the largest UHECR experiment in operation, combines the two techniques, with arrays of particle detectors overlooked by fluorescence detector (FD) telescopes. Auger covers an area of over 3000 km^2 close to the town of Malargüe in the province of Mendoza, Argentina. The Telescope Array experiment (TA) [4,5] is the second largest experiment in operation and uses the same detection techniques as Auger. TA is located near the town of Delta in central Utah, USA, and covers an area of 700 km^2. The High Resolution Fly's Eye experiment (HiRes) [6], which consisted solely of FD stations (HiRes-I and HiRes-II), was operated from 1998 to 2006 on the U.S. Army's Dugway Proving Ground in western Utah.

Significant advances in our understanding of UHECRs have been achieved in the last decade by these experiments [7]. The existence of a strong suppression of the cosmic ray flux above 10$^{19.7}$ eV is now unequivocally established [8,9]. This observation is consistent with UHECRs being attenuated by interaction with the cosmic microwave background over distances of $\sim$ 100 Mpc, as predicted by Greisen, Zatsepin and Kuzmin (GZK) [10,11] in 1966. However, a cutoff in the spectrum of UHECRs at the accelerating sources may also offer an explanation. The mass composition reported by Auger through $X_{\max}$

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(the depth in the atmosphere at which the EAS reaches its maximum energy deposit) suggests a transition from light nuclei at around $10^{18.3}$ eV to heavier nuclei up to energies of $10^{19.6}$ eV [12,13]. The mass composition reported by TA and HiRes is lighter, and consistent with a protonic composition for cosmic rays with energies greater than $10^{18.2}$ eV [14,15]. However, mean $X_{\rm max}$ values observed by both Auger and TA are compatible within statistical uncertainties [16,17]. No evidence for photons or neutrinos in the UHECRs has been found thus far [18–20]. Arrival directions of UHECRs are found to correlate with nearby extragalactic objects at a modest $2-3\sigma$ significance level [21,22]. Recently, TA has reported evidence of a hotspot in the northern hemisphere with a 3.4σ post-trial significance [23].

These results are limited by statistics at the highest energies due to the GZK-like suppression. To further advance the field, the next generation of experiments will require an aperture which is larger by an order of magnitude. This may be accomplished by the fluorescence detection of UHECR showers from space, as in the proposed JEM-EUSO [24] mission, or with a ground array much larger than Auger. Low-cost, easily-deployable detectors will be essential for a ground-based experiment.

In this paper, we present an FD telescope concept which would fulfill these requirements, while maintaining adequate energy, $X_{\rm max}$ and angular resolution. The Fluorescence detector Array of Single-pixel Telescopes (FAST) would consist of compact FD telescopes featuring a smaller light collecting area and many fewer pixels than current generation FD designs, leading to a significant reduction in cost. The FAST design may be an attractive option not only for future UHECR experiments, but also for upgrades of existing UHECR observatories. For example, it could provide low-cost fluorescence detector coverage to the fourfold expansion of the TA experiment [25], and be used at the Pierre Auger Observatory to increase the number of showers detected in stereo with more than one telescope. We present the FAST concept and its expected performance from simulations in Section 2. The FAST prototype installed at the TA site is described in Section 3, with details of its operation and calibration given in Section 4. Detection of UHECR showers with the FAST prototype is reported in Section 5. Finally, conclusions are drawn in Section 6.

2. FAST concept and expected performance

In the current Auger FD telescope design, a mirror system (effective light collecting area $A \sim 3$ m^2) reflects a $\sim 30° \times 30°$ patch of the sky onto a focal plane composed of 440 40 mm photomultiplier tubes (PMTs) [3]. In the FAST design, the same field of view (FOV) is covered by just a few $\sim$ 200 mm PMTs at the focal plane of a mirror or Fresnel lens of $A \sim 1$ m^2. We expect a significant cost reduction thanks to FAST's compact design with smaller light collecting optics, a smaller telescope housing, and a small number of PMTs and associated electronics. We estimate that the FAST reference design – a telescope of 1 m^2 effective area with a $\sim 30° \times 30°$ camera consisting of four PMTs – could cost less than 10% of a current generation FD telescope with the same FOV coverage. In this work, we focus our simulation and experimental efforts on the reference design, as it is the most cost effective for detection of the highest energy showers ($>10^{19.5}$ eV). Increasing the number of PMTs would result in higher costs, with the primary gain being a lower energy threshold and improved efficiency and resolution at lower energies where large statistical samples have already been collected by current generation FDs. FAST stations, powered by solar panels and with wireless connection, could be deployed in an array configuration to cover a very large area.

The proposed FAST design differs notably in operation from present generation FDs in two ways. The average current produced by the night-sky background (NSB) in a fluorescence detector PMT is proportional to $A\Delta\Omega$, where $\Delta\Omega$ is the pixel solid angle. In our design, $A_{\rm FAST} \sim 1$ m^2 and the pixel opening angle is $\sim 15°$, compared with typical values of ~ 3 m^2 and $\sim 1.5°$ for the Auger FD, or ~ 7 m^2 and $\sim 1°$ for the TA FD. This means that FAST pixels will operate under significantly higher current. In addition, the relatively small detector aperture and large pixel solid angle leads to an increased energy threshold for UHECR detection, as the signal to noise ratio is proportional to $\sqrt{A/\Delta\Omega}$. The second major difference relates to shower geometry reconstruction. As current generation FD cameras consist of several hundred PMTs each viewing a small portion of the sky, a detected shower is seen as a line of triggered pixels which define what is known as the shower-detector plane. The shower orientation within this plane can then be determined either from the pixel timing information via a χ^2 minimization, or via the intersection of two or more shower-detector planes if the same shower is seen by more than one FD station. As the proposed FAST design consists of only a few pixels, each viewing a large portion of the sky, geometry reconstruction of the shower detector plane in this manner is not possible. FAST would therefore need to be operated alongside a surface detector which independently provides the EAS geometry. Alternatively, a FAST-only reconstruction may be possible by combining measurements from several FAST stations. For a shower that triggers multiple FAST stations, the measured signals can be used to constrain the shower geometry. In this case, a ground array of water-Cherenkov tanks or scintillators would not be required, further reducing the cost. The potential of this geometry reconstruction method is currently being investigated, and will be reported elsewhere. We foresee a trigger and data acquisition system similar to that of current generation SD arrays: a first level trigger operating at a rate of 20–100 Hz optimized for microsecond long pulses will be implemented in each FAST PMT, with the corresponding digitized data kept locally in a circular buffer of several seconds depth. FAST stations will send their trigger information to a central location which will reply with a readout request when appropriate conditions are met (e.g. the timing from different FAST stations is consistent with a shower candidate).

We have performed extensive simulations to study the performance of the FAST design with a geometry reconstructed by a surface array. Our reference telescope has an effective area of 1 m^2 and a $30° \times 30°$ FOV camera consisting of four PMTs. A FAST station consists of twelve such telescopes, covering 360° in azimuth. We present simulations for a triangular arrangement of FAST stations with a spacing of 20 km. UHECR showers were generated with CORSIKA [26], and a modified version of the Auger $\overline{\rm Off}\underline{\rm line}$ software [27] was used for the FAST telescope simulation and shower reconstruction. Since the design of the telescope is not yet finalized, a generic telescope was simulated, which included an effective light collecting area of 1 m^2, a mirror, a UV band-pass filter, and four PMTs. The wavelength dependence of the mirror reflectivity, the UV filter transmission, and the PMT quantum efficiency were included in the simulation. Simulated showers were thrown following a realistic zenith angle distribution, and cores were placed randomly within a circle of radius 10 km in the center of the triangular arrangement at an altitude of 1400 m above sea level. Emission of fluorescence photons in proportion to the shower energy deposit along its path in the atmosphere was simulated according to precise laboratory measurements of the fluorescence yield [28,29]. Light attenuation in the atmosphere due to Rayleigh and Mie scattering was included in the simulation. Lastly, fluctuations in the PMT signal due to the night-sky background were included. Atmospheric attenuation parameters and a NSB level typical of the Auger and TA sites were assumed.

An example of a simulated FAST event is shown in Fig. 1. To reconstruct shower parameters from the FAST signal, the shower geometry must be given by a surface array. For the sake of simplicity, we did not simulate such an array, but rather took the true geometry of the simulated shower and smeared it by 1.0° in arrival direction and 100 m in core location, which are typical resolutions of existing UHECR surface arrays (e.g. [30]). Given the geometry, the energy deposit profile at the shower axis is reconstructed by unfolding the detector efficiency and the atmospheric attenuation. The energy and