

# ULTRAHIGH ENERGY COSMIC RAYS: REVIEW OF THE CURRENT SITUATION

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**ABSTRACT.** We describe the current situation of the data on the highest energy particles in the Universe – the ultrahigh energy cosmic rays. The new results in the field come from the Telescope Array experiment in Utah, U.S.A. For this reason we concentrate on the results from these experiments and compare them to the measurements of the other two recent experiments, the High Resolution Fly’s Eye and the Southern Auger Observatory.

**KEYWORDS:** high energy cosmic rays, hadronic interaction at very high energy, origin of the highest energy cosmic rays.

## 1. INTRODUCTION

Two years ago I was asked to review at this meeting the new results of the measurements of the ultrahigh energy cosmic rays (UHECR). At that time there were two experiments that performed such measurements: the High Resolution Fly’s Eye (HiRes) in Utah, U.S.A., and the Auger Southern Observatory (Auger) in Mendoza, Argentina. HiRes is a detector that measures the fluorescent light emitted by the nitrogen in the atmosphere when its atoms are excited by the numerous electrons of such large air showers. Its two fluorescent telescopes are able to detect showers that hit the ground up to distances of 40 km from the detectors. The two telescopes of HiRes can observe the air showers separately or in stereo mode with both telescopes. Auger is a hybrid experiment that combines four fluorescent detectors (FD) with a huge surface array (SD) that covers 3000 km<sup>2</sup>. The surface array consists of 1600 water Cherenkov tanks on a triangular matrix with an average distance between the tanks of 1500 m. The Cherenkov tanks are deep enough (almost three radiation lengths) to detect electrons, gamma rays, and muons, and thus measure the energy flow of the air shower.

A brief summary of the results at that time is that both detectors observed the GZK feature in the UHECR energy spectrum [5, 14]: the steep decline in the UHECR energy spectrum above energy of  $4 \times 10^{19}$  eV due to the energy loss in cosmic ray propagation from their presumably extragalactic sources to us. The two measured spectra have very similar shapes and agree with each other within systematic errors of about 20%. The two experiments, however, did disagree on the chemical composition of UHECR: HiRes interpretation of the measured depth of shower maximum ( $X_{\max}$ ) and its fluctuations was that all UHECR are hydrogen nuclei (protons) [10], while Auger interpreted its results as a chemical composi-

tion becoming increasingly heavier with energy above  $2 \times 10^{18}$  eV [6]. The interpretation of the chemical composition from the  $X_{\max}$  measurement depends on the hadronic interaction model used, which creates a significant systematic error.

Auger also saw a correlation of their highest energy events (above 55 EeV =  $5.5 \times 10^{19}$  eV) with nearby AGN, while the smaller HiRes statistics did not show any correlation. These results have not changed during the last two years.

### 1.1. TELESCOPE ARRAY

The new results come from a new detector, the Telescope Array (TA), which is a hybrid detector that started collecting data in 2009 in Utah, USA, at 39°N, 120°W and an altitude of 1500 m. Its surface array (SD) consists of 607 scintillator counters on a square grid with dimension of 1.2 km. Each scintillator detector consists of two layers of thickness 1.2 cm and area of 3 m<sup>2</sup>. The phototube of each layer is connected to the scintillator via 96 wavelength shifting fibers, which make the response of the scintillator more uniform. Each station is powered by a solar panel that charges a lead-acid battery. The total area of the surface array is 762 km<sup>2</sup>. The surface array is divided into three parts that communicate with three control towers where the waveforms are digitized and triggers are produced. Each second, the tower collects the recorded signals from all stations and a trigger is produced when three adjacent stations coincide within 8 μs. The SD reaches full efficiency at  $10^{18.7}$  eV for showers with zenith angle less than 45° [9]. This angle corresponds to SD acceptance of 1600 km<sup>2</sup> sr.

The fluorescence detector (FD) consists of three fluorescence stations. Two of them are new and consist of 12 telescopes with field of view from elevations of 3° to 31°. The total horizontal field of view of each station is 108°. The third station has 14 telescopes that use cameras and electronics from HiRes-I and

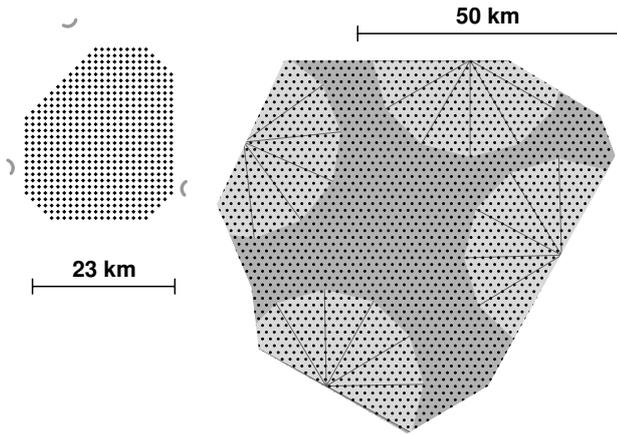


FIGURE 1. Comparison of the sizes of the surface arrays of the Telescope Array and the Auger Southern Observatory. The positions of the TA fluorescent detectors are indicated with small arcs.

mirrors from HiRes-II. The fluorescent telescopes are calibrated with  $N_2$  lasers, Xe flashers, and an electron linear accelerator [11].

The atmosphere is monitored for clouds by IR cameras and with the use of the central laser facility, which is in the center of the array at 20.85 km from each station. The fluorescent stations are positioned in such a way that they cover the whole area of the surface detector. The mono acceptance of the FD is  $1830 \text{ km}^2 \text{ sr}$  and the stereo acceptance is  $1040 \text{ km}^2 \text{ sr}$ . The total energy resolution is 25% and the  $X_{\text{max}}$  resolution is  $17 \text{ g/cm}^2$ .

## 2. NEW RESULTS

The new results come from the Telescope Array. They were reported at the 2011 International cosmic ray conference in Beijing. Two papers also appeared in the arXiv a couple of months ago. Figure 1 compares the size of the TA to that of Auger – it is almost four times smaller. In addition, the water Cherenkov tanks have the same effective area up to a shower zenith angle of  $60^\circ$  which means that their exposure is higher than that of the scintillator counters. For these reasons the new TA results are based on smaller statistics and should be considered preliminary.

### 2.1. UHECR ENERGY SPECTRUM

Figure 2 shows the energy spectrum measured by the Telescope Array [3] compared to the spectra of Auger and the HiRes experiments. At first glance at the figure, we see that the spectrum measured by TA is extremely close to that of HiRes. One should say here that there is a big difference between the way the energy spectrum is measured by the two detectors. The Telescope Array uses the method of measuring the energy spectrum with the surface array introduced by Auger. Fluorescent telescopes can work only on clear moonless nights with good atmospheric conditions (about 10% of the time) while surface arrays are

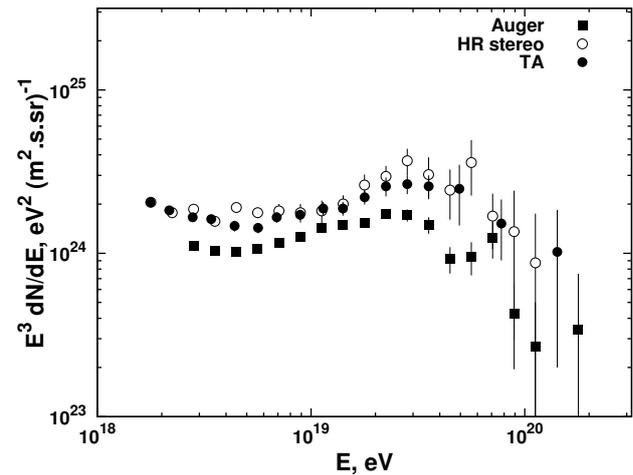


FIGURE 2. Energy spectrum of the UHECR measured by TA, HiRes and Auger. The particle flux is multiplied by  $E^3$  to show better the shape of the energy spectrum.

active all the time. In addition, the energy estimates with the surface array depend heavily on the hadronic interaction model used in the shower analysis. To increase the statistics, one can correlate the particle density in the surface array at a certain distance from the shower core (800 m for TA and 1000 m for Auger) with the energy estimate from the fluorescent detectors (which does not need the hadronic Monte Carlo) and then use the surface density to obtain the spectrum.

The Telescope Array energy spectrum paper [3] also fits the shape of the spectrum with a broken power law. The *ankle* of the spectrum, where it becomes less steep, is at  $(4.8 \pm 0.1) \times 10^{18} \text{ eV}$ . The power law index  $\alpha$  before the ankle is  $3.33 \pm 0.04$ , at the ankle it is  $2.68 \pm 0.04$ , and at the GZK decline it is  $4.2 \pm 0.7$ . The statistics is, of course, quite small but there is no doubt that the spectrum becomes steeper, as predicted by Greisen and Zatsepin&Kuzmin. It is indeed remarkable that using very different methods for observation of the spectrum the data of TA and HiRes agree so well.

One has to admit that the shape of the energy spectrum detected by TA is also very similar to that of Auger in spite of the different normalization. All three spectra shown in Fig. 2 are consistent within the systematic errors claimed by the experiments, which are of the order of 20%.

### 2.2. CHEMICAL COMPOSITION OF UHECR

The measurement of the chemical composition of cosmic rays is through the interpretation of the depth of shower maximum  $X_{\text{max}}$ . The position on the shower maximum for proton showers becomes deeper in the atmosphere with energy because showers continue developing until the average energy of its particles decreases below 80 MeV. Showers caused by heavy nuclei have  $X_{\text{max}}$  higher in the atmosphere because in the first approximation they are the sum of  $A$  nucleon showers of energy  $E/A$ . At energies above  $10^{18} \text{ eV}$  the

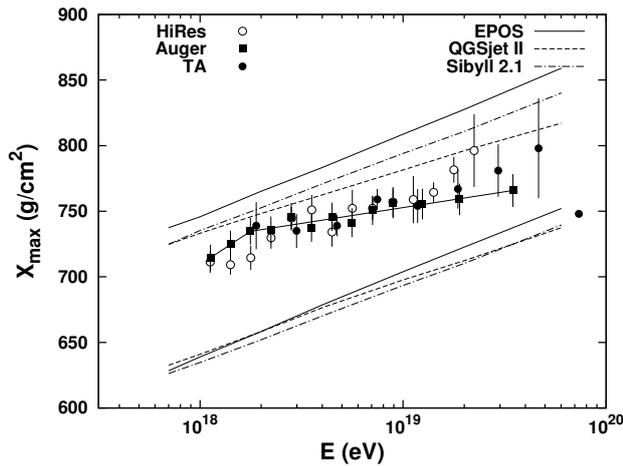


FIGURE 3. Depth of shower maximum measurements by the Telescope Array, HiRes and Auger. The lines show the energy behavior for proton and iron showers for three hadronic interaction models.

difference between  $X_{\max}$  of proton and iron showers is about  $100 \text{ g/cm}^2$ . The primary mass of the particle interacting in the atmosphere also affects the fluctuations of  $X_{\max}$  per energy bin. Showers caused by heavy nuclei would have smaller fluctuations, as in the simplest model (superposition) the fluctuations in such showers should decrease by  $\sqrt{A}$ . In Monte Carlo calculations the difference is smaller, varying from about  $60 \text{ g/cm}^2$  for proton showers to about  $20 \text{ g/cm}^2$  for Fe showers.

Figure 3 compares the  $X_{\max}$  measurements of the Telescope Array [12] presented at the 2011 International Cosmic Ray Conference (Beijing) with the results of HiRes and Auger.

The interpretation of the  $X_{\max}$  measurement by the TA experiment is that the UHECR composition is light, consisting mostly of protons and very light nuclei. It is not easy to understand the very different interpretations of the data of HiRes and TA, on one hand, and Auger, on the other hand, of data look very similar to the naked eye. The explanation of the previous disagreement between HiRes and Auger was that they used different event selection. It is not obvious now what exactly the TA event selection is. One has to have in mind that the highest energy two points in its data set have respectively only three and one events and the average  $X_{\max}$  could be different when more statistics is collected.

The Telescope Array also presented [12] the distributions of  $X_{\max}$  in the energy bins shown in Fig. 3. At relatively low energy, the widths of the distributions were more similar to proton showers, while at high energy the statistics is not enough to judge the distributions.

### 2.3. IDENTIFYING THE SOURCES OF UHECR

In 2007 the Auger Collaboration published a paper where a correlation of their highest energy events ( $> 55 \text{ EeV}$ ) with AGN was discussed. At that time

the collaboration had seen 27 such events. Eighteen of these events had an angle of less than  $3.2^\circ$  from the positions of nearby (redshift  $z < 0.018$ , distance less than 75 Mpc) AGN from the Véron-Cetty and Véron catalog (VCV) [13]. The correlation was even stronger if events close to the galactic plane were excluded. Although the VCV catalog contains mostly not very powerful Seyfert-2 AGN, they may have marked the the distribution of the real sources. This paper had a huge readership and many scientists were convinced that the sources of UHECR would be discovered soon. The HiRes data (13 events) did not confirm this correlation [1] and papers discussing the different fields of view (Auger in the South and HiRes in the North) appeared in press.

Since the Southern Auger Observatory was completed at that time it did not take long to significantly increase the statistics. In 2009 the correlation of 69 high energy events with the same AGN catalog was published. The correlation has decreased to about 38% of the events. The previous result happened to be a typical  $3\sigma$  disappearing result.

The disagreement between Auger and HiRes on the correlation of the arrival directions of their highest energy events with AGN is also strange, because of their results on the chemical composition of UHECR. If the composition is indeed heavy, as interpreted by Auger, one expects that the heavy nuclei would scatter more in the intergalactic and galactic magnetic fields and show no anisotropy.

Figure 4 shows the arrival directions of the highest energy events of Auger, HiRes and TA. Having in mind the dimensions of Auger and the TA (see Fig. 1) and the fact that TA field of view is restricted to zenith angles less than  $45^\circ$ , it is difficult to believe that the ratio of their statistics is less than three. We hope that Auger has more than 100 such events by now. The 20% difference in the energy assignment may also play a role in this issue.

It is not easy to judge what the new data set says about the correlation of the UHECR arrival direction with powerful astrophysical sources. One way would be to judge the possible direction of the sources by close-by arrival directions of groups of highest energy events. We looked at pairs of events at angular distance less than  $5^\circ$  from each other. There are 11 such pairs in the Auger 69 events data set. Six such pairs are within 18 degrees of CenA. An isotropic Monte Carlo in the Auger field of view creates on the average 11 pairs, the same number as in the data. There are three pairs consisting on HiRes and Auger events and one TA-Augur pair. There are also two pairs consisting of TA events, as shown in Fig. 4. It is not possible to run an isotropic Monte Carlo for the new events because the exposure of the Telescope Array is not as well defined as those of Auger and HiRes.

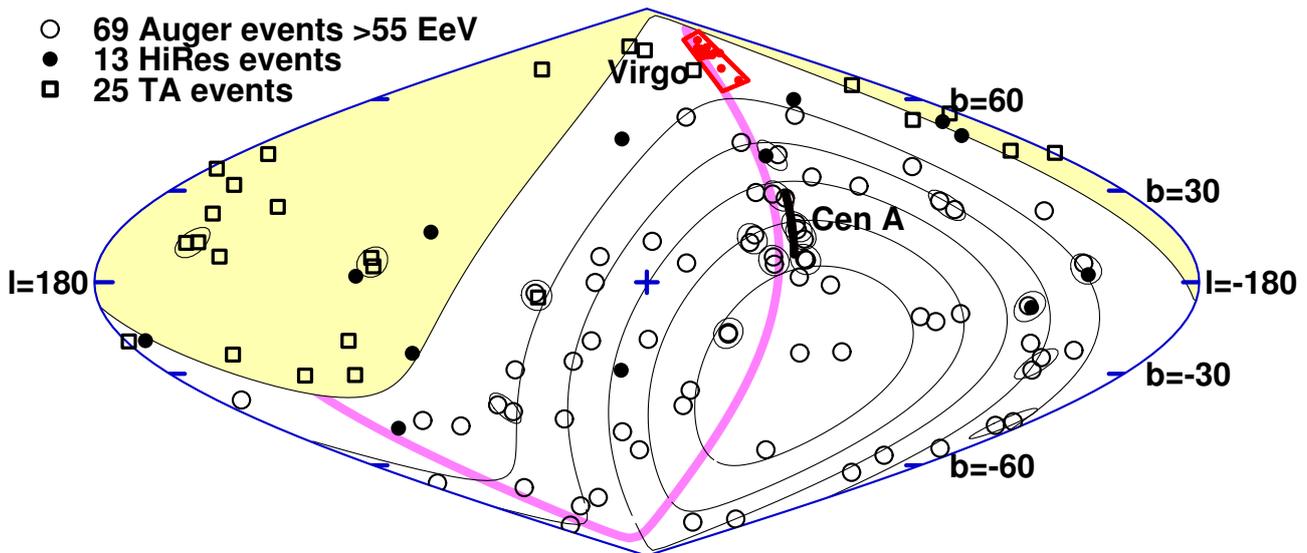


FIGURE 4. Arrival directions of the 69 Auger events, 13 HiRes events and the TA 25 events in galactic coordinates. The colored area shows the part of the Galaxy that Auger does not see. The six areas defined within the Auger field of view have equal exposures. The events that form a pair at angular distance less than  $5^\circ$  are circled.

### 3. DISCUSSION

It is not possible to conclude anything new from the data set of the Telescope Array. Its results on the energy spectrum of the UHECR are very similar to those of the High Resolution Fly's Eye. All three newest experiments confirm the end of the cosmic ray spectrum that is consistent with the GZK effect and with photo dissociation energy loss of heavy nuclei. The three published spectra are almost identical within the stated systematic error of more than 20%. It may be important for high energy physics to understand the differences, claimed by Auger and TA, between the energy assignment of the events from the fluorescent detectors and the surface arrays, which is also of the order of 20%. The analysis of the surface array data in both detectors gives a higher energy assignment.

In the case of Auger, the suspicion is that the water Cherenkov tanks of the surface array see a much higher number of muons, which produce more light in the tanks than electrons and  $\gamma$ -rays do. In the case of TA the surface array consists of scintillator counters where muons generate the same signals as electrons do. In this case a wrong expectation about the shower muons would make a smaller contribution to the energy assignment.

By far the biggest controversy in the results is the interpretation of the  $X_{\max}$  measurement by the three experiments shown in Fig. 3. The results of the measurements do not seem to be as different to the eye as the interpretation is. HiRes and TA interpret the results as an almost purely proton composition, while Auger interprets the measurements as a composition becoming increasingly heavier with energy. In the review of UHECR [8], suspicion fell on the different event selection in Auger and HiRes. We do not know much about the selection in TA yet, and this question is still open.

There is some theoretical contradiction between the chemical composition derived by Auger and the anisotropy it has measured, including the large number of events coming from the vicinity of CenA. Lemoine & Waxman [7] suggested that if the composition were heavy there would be protons from nuclear photodissociation that would show the same anisotropy at significantly lower energy. Such anisotropy at about  $10^{18}$  eV has not been seen by the Auger experiment. This is not an argument against the heavy composition derived by Auger, but an interesting argument for further measurements and observations.

The new data on the arrival direction distribution of UHECR that come from TA did not contribute to the source identification. It is very good though, to have an active experiment in the Northern Hemisphere. Auger and TA are able to increase the statistics by a factor close to five during the next four years. This statistics may not be sufficient to identify of the sources of the ultrahigh energy cosmic rays, but it will certainly be an improvement over the current situation.

The good news is that at the International Symposium on Future Directions in UHECR physics at CERN in February 2012 the two collaborations started to work together on all of the topics discussed above. Working groups consisting of members of both collaborations were created and gave talks at the symposium. All of us hope that the working groups will make a good study of the differences in the shower reconstruction and data analysis, and will at least discover the reasons for the contradictory results. If this happens, we will know much more about this exciting field in a couple of years.

## ACKNOWLEDGEMENTS

The author thanks the organizers of the Vulcano workshop for the invitation to this excellent and useful meeting. His work is supported in part by DOE grant DE-FG02-91ER40626.

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## DISCUSSION

**Peter Grieder** — Concerning the differences in composition between Auger and the Telescope Array. The two experiments see different sources. These maybe of different nature. Please comment.

**Todor Stanev** — The fields of view of Auger and TA are different, but it is difficult to imagine that the cosmic ray composition that much. The fields of view of Auger and HiRes coincided about 30 % so HiRes should have seen some heavy nuclei. I do not believe that this is the reason for the disagreement.

**Laurence Jones** — We now know that the total p-p cross section rises to about 100 mb near 1 EeV. Do the Monte Carlo models used to determine the mass include the cross section rise?

**Todor Stanev** — The hadronic Monte Carlo models used for shower analysis have a rising cross section. The cross section of SIBYLL 2.1 is higher than the one measured at LHC. All interaction models are now revised to match the measurements.

**Anatoly Erlykin** — Will the extreme sharpness of the ankle in the published Telescope Array surface array energy spectrum be an evidence against the dip model of its origin?

**Todor Stanev** — The first point of the TA energy spectrum is indeed quite high. Since it is only one point at the detector threshold, where the detector is not fully efficient, I have not paid much attention to it.