The Pierre Auger Observatory - what astrophysical problems is it going to solve ?

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1 Introduction

The ultra-high energy cosmic rays (UHECR) are a real puzzle for astrophysicists. They are observed by producing huge showers of secondary particles, developing in the atmosphere and hitting the earth. It is the French physicist, Pierre Auger, who first discovered this phenomenon in 1938. The energies of the primary particles producing the showers reach well above $10^{19} eV$ and it is just this energy range which is most intriguing. It turns out that we can predict more about the UHECR than about those of lower energies: One prediction, known since 1966 [1] is that if UHECR were extragalactic then their energy spectrum should cut off rather dramatically at about $5 \cdot 10^{19} eV$ due to setting on of the cosmic ray interactions with the universal microwave background (and also other intergalactic radiation backgrounds). Thus, measuring the UHECR energy spectrum would provide an important clue to their origin : Galactic or extragalactic. Another advantage of dealing with UHECR is that their propagation in the space is much less sensitive to the ambient magnetic fields (Galactic and/or extragalactic), so that their arrival directions should (more or less) point to their sources, so far unknown. In this paper we will describe the present experimental situation of the UHECR and show the necessity of further measurements. Then the Pierre Auger Observatory (being currently built), its experimental possibilities, illustrated by some first results, will be presented. We hope that the answer to the question in the title will be eventually clear.

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2 The present experimental status of UHECR

2.1 The energy spectrum

The energy of a cosmic ray particle in the range in question ($E > 10^{19} eV$) can only be derived indirectly - by examining properties of the extensive air shower it produces in the atmosphere. There exist two main methods of doing this. One is to determine the number of shower particles at the earth surface (by installing particle detectors on it), or particle density at a given distance from the shower core. By comparing these with values obtained by numerical simulations of shower development with known primary energy, one gets an estimation of it. Another method is to detect fluorescence light emitted by the atmosphere excited by the shower charged particles (mainly electrons and positrons). It can only be measured at night as the fluorescence flash is rather weak, but the pulse time (and direction) profiles tell us about number of shower particles not only at the earth surface but along the whole shower track in the atmosphere. The estimation of the primary energy in this case is almost independent of the details (unknown) of the high energy interaction models, as in the previous case.

The most recent results come from the two experiments: AGASA in Japan, using the first method [2], and HiRes in USA using the second one [3]. The energy spectra determined by these experiments, together with older data from Haverah Park in UK [4] are presented in Fig.1. It is obvious that the conclusion about the GZK cutoff can not be drawn from this graph. The data points for $E > 5 \cdot 10^{19} eV$ show different trends : the AGASA spectrum turns up whereas the HiRes one goes down. There is also evident some systematic shift in the spectra of the two experiments, but even if this is eliminated the discrepancy at the highest energies remains and the problem whether there is the cutoff in the spectrum stays unsolved.

The determination of the UHECR spectrum is not an easy task: above some $5 \cdot 10^{19} eV$ the cosmic ray flux drops to about a few particles per $100\, km^2$ per year, so that very large areas have to be covered by detectors to collect statistically meaningfull samples (AGASA registered air showers from $100\, km^2$ with 111 scintillator detectors for several years and detected 12 events with the estimated by them energy above $10^{20} eV$). To determine the cosmic ray flux one also has to determine the acceptance of the whole detector, which can be evaluated by numerical simulation of the detector response. In the second method (by detecting the shower fluorescence light) detailed knowledge of the light attenuation and scattering in the atmosphere is necessary to calculate the acceptance. In what follows (section 3) we shall show that the Pierre Auger Observatory will collect much more statistics and will be able to determine the shower primary energy in a more reliable way than it has been done so far.

2.2 Arrival directions

To determine the arrival direction of a shower one uses the fact that it travels through the atmosphere as a thin disk of relativistic particles, perpendicular to the direction of the primary particle (shower axis). The delays of particle arrival times to different detectors allow then to determine the direction of the axis. In the experiments detecting the fluorescence light it is the time profile of the light signal which allows to calculate the shower geometry. Fig.2 shows the measured arrival directions of the UHECR in galactic coordinates. It is obvious that there is no apparent anisotropy seen on the map. If UHECR were of the Galactic origin then at these energies one would expect an excess of particles from the Galactic plane. So, the extragalactic origin seems to be supported. But then one should observe a cutoff in the energy spectrum, which is far from obvious (Fig.1). Again, more data are needed to measure more accurately the arrival direction map (and some possible large scale anisotropy with a small amplitude) and find a consistent picture of UHECR origin.

There is also hope that these high energy particles, little affected by cosmical magnetic fields, will point out to their sources (if they are close and/or strong enough). A hint of such a possibility comes from the AGASA data [6]. They have registered one triplet of events (three showers from the same direction, within the angular resolution) and 6 doublets, with a small probability of these being statistically allowed by isotropy. More data will certainly be more conclusive about the observed small scale excesses (multiplets). If a multiplet can be associated with a cosmic object (by small angular distance) then a new possibility about studying Galactic and extragalactic magnetic fields opens up (see eg. [7]). The large scale Galactic field would shift the particle arrival directions proportionally to their charge to energy ratio and the perpendicular field integral along the particle trajectory. Assuming primary protons and measuring their energies one can determine this integral. If the sources were extragalactic then we could obtain information also about the extragalactic magnetic field (believed to be irregular). The shifting of particle directions would be then a random variable with the distribution dependent on the product of the field rms and the square root of the irregularity scale.

3 The Pierre Auger Observatory

The goal of the Pierre Auger Observatory (PAO)[8] is to measure the cosmic ray energy spectrum ($E > 10^{18} eV$), the arrival direction distribution and (possibly) the masses of primary particles over the whole sky, with a much better accuracy that it has been done so far. A necessary condition to achieve this is to collect statistically significant sample of UHE showers. In particular, to increase number of events in the cutoff region by an order of magnitude , one needs an order of magnitude larger area covered by detectors. PAO will consist of two parts , one in each of the Northern and Southern hemispheres, each consisting of $3000\,km^2$ covered by 1600 water Cherenkov detectors (Fig.3), spaced by $1.5\,km$, to detect shower particles. It is expected that the fully operating array will register several tens of showers per year with $E > 10^{20} eV$. As it is planned to work for some 20 years the statistics of the highest energy particles will be sufficient to resolve the cutoff puzzle.

The detector array will be overlooked by four optical stations, each containing six telescopes to detect fluorescence light (with angular resolution of 1.5°) excited by shower particles in the atmosphere (Fig.4). Thus, PAO will be able to determine the primary energy of some 10% showers (those detected by night and by clear atmospheric conditions) by the two independent methods described above. For the first time there will be a check of the systematic errors made in the primary energy determination , resulting (hopefully) in their elimination ! However, to do so a continuous checking of the atmospheric transparency is necessary, in particular its aerosol containment. PAO does have several instruments to perform the necessary measurements.

The field of view of the two sites (on both hemispheres) will cover almost uniformly the whole sky. So far the Southern hemisphere was poorly known but now, it is there (in Argentina) that PAO has started. The whole sky coverage is very important for determination of weak large scale anisotropies (eg.dipol, quadrupole) which might be an important clue to the particle origin [9]. The angular resolution in determining shower direction will be much improved due to detailed study of the particle detector signals and allowing for some curvature of the shower front. For the showers registered by the fluorescence detectors there will be an additional, independent determination of their directions. The angular accuracy depends on the shower primary energy (improving with it), but should be about $0.2°$ for the largest showers. It is about an order of magnitude better than in the AGASA experiment. The accurately measured arrival directions are crucial when looking for point sources. Also the determination of the cosmic magnetic fields , both Galactic and extragalactic (see above) could be made with meaningful results only if the particle directions are known to within a fraction of a degree.

4 Some first results of PAO

At present (October 2004) there are about 500 water Cherenkov detectors installed in Pampa Amarilla, the Southern site of PAO in Argentina. There are also two (of the four) fluorescence detectors operating. The array has been collecting data and we will illustrate its performance by showing some examples of the registered showers. Fig.5 presents a shower as registered by the fluorescence detector (FD). The lower left panel shows the angular image of the shower on the sky - the black dots represent the hit photomultipliers, out of 440 of them located at the telescope focal plane. The lower right panel shows the arrival time of the fluorescence light as a function of the elevation angle of the emitting shower track, seen by consecutive pixels. The upper panel presents the reconstructed longitudinal profile of the shower, ie. number of charged particles as a function of the slant path (in $g \cdot cm^{-2}$) traversed by the shower. The distance of the shower track from the detector was about $24.4\,km$ and the estimated primary energy about $5 \cdot 10^{19} eV$. Fig.6 shows a hybrid event, ie. detected by both types of detectors. The FD camera is represented here by an array of hexagons (the shape of the PMT windows). The shower track is thicker than in the previous case as the shower is less distant (about $9.8\,km$). The upper right panel shows a part of the surface array, where the large circles represent the hit particle detectors (ten). The lateral distribution of the detector signal (roughly proportional to the number of particles hitting the detector) is shown on the lower panel, together with the fitted curve. In this experiment it is the particle density at $1000\,m$ from the shower core that is the measure of the primary energy from the surface detectors. For this particular shower the preliminary estimations of the shower energy from both types of detectors are quite close ($2.17 \cdot 10^{19}$ and $1.93 \cdot 10^{19} eV$), giving confidence to the performance of the experiment and the reconstruction procedures applied. Another hybrid example in shown in Fig.7. but this time the shower was seen by two adjacent telescopes (view of the two cameras is seen). There were twenty surface detectors hit but, as the shower was quite inclined (its zenith angle was about 68°) the pattern of the hit detectors is elongated. The lateral distribution function allows to determine the primary energy as $4.5 \cdot 10^{19} eV$. However the cascade curve (not shown) from the fluorescence detector is not reliable enough to do so.

5 Conclusions

We have described the possibilities and illustrated the performance of Southern Site of the Pierre Auger Observatory, being presently in construction. It is already the largest shower array ever existed and will cover about 30 times bigger area than the latest Japanese experiment AGASA. Due to expected large statistics and the hybrid way of registering a fraction of showers , the cosmic ray energy spectrum in the region $E > 10^{18} eV$ will be determined with unprecedented accuracy. The full sky coverage (once the Northern Site will operate) will allow to measure large scale anisotropy (if any) in particle arrival directions and detect (possibly) some nearby strong sources of these particles.

There remains the question of measuring the mass of primary particles to be discussed. There are protons and iron nuclei at the two extremes of the mass spectrum and so far not much really convincing can be stated about primary composition of the UHECR (but see, however, [11]) . The information about it can be obtained by studying atmospheric depths of shower maxima , X_{max}. Iron induced shower develops higher in the atmosphere, whereas number of shower particles in the shower maximum is (practically) the same for a proton shower with the same energy. As we have seen on Fig.5 and 6, the fluorescence detector allows to determine the shower longitudinal profile, meaning also X_{max}. By measuring its values and fluctuations (X_{max} for iron showers fluctuates much less) it should be possible to determine on which side of the mass scale are the primary particles. A detailed study of the time shapes of signals from the surface detectors can also be a method for primary mass determination [8]. Thus, again there are two independent methods to determine particle masses , although this can only be done on the statistical basis. The Auger experiment can also measure neutrino induced showers (showers highly inclined or from below the horizon) [10].

All these experimental efforts serve, of course, our quest to understand the origin of ultra-high energy cosmic rays: where they are produced (exclude our Galaxy?) and what cosmic objects are their sources. Only knowing this we can be more confident in the proposed mechanisms of particle producion (eg. if UHECR turn out to be heavy nuclei it will exclude all the exotic models of their production, such as decay of topological defects). A very extensive and comprehensive review of all aspects of the UHECR subject is presented in the review by Nagano and Watson [12].

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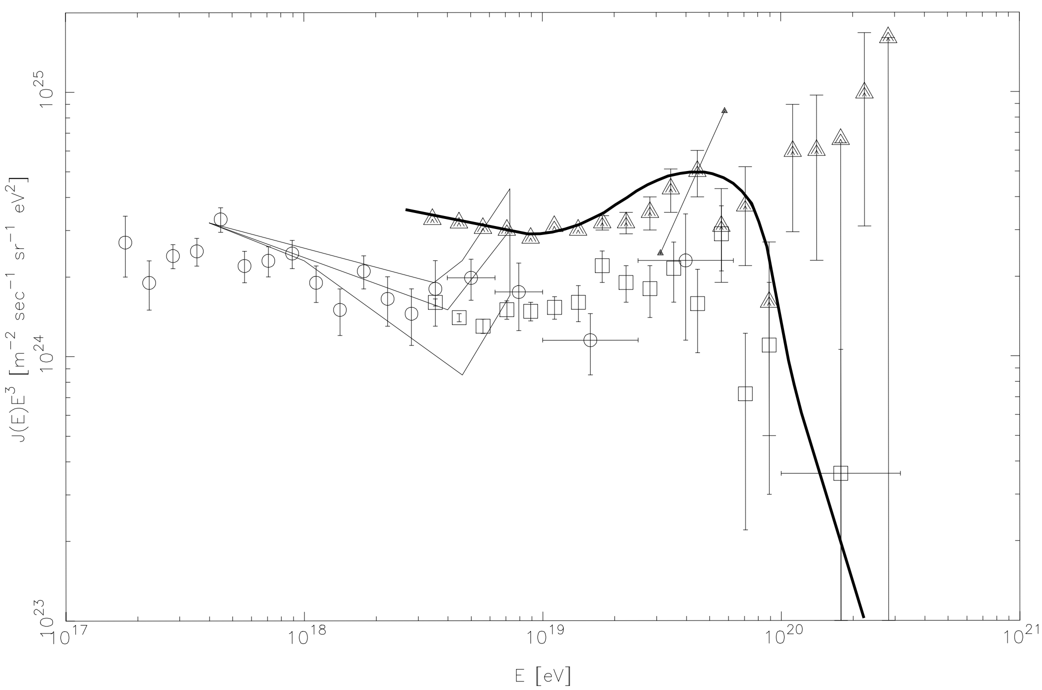

Figure 1: Differential energy spectrum of UHECR multiplied by E^3 as measured by HIRes I (squares) and HiRes II (circles), AGASA (triangles) and Haverah Park (region marked by thin lines). The thick line are the predictions for extragalactic sources distributed uniformely in the universe [5], normalised to the AGASA data at $1 \cdot 10^{19} eV$.

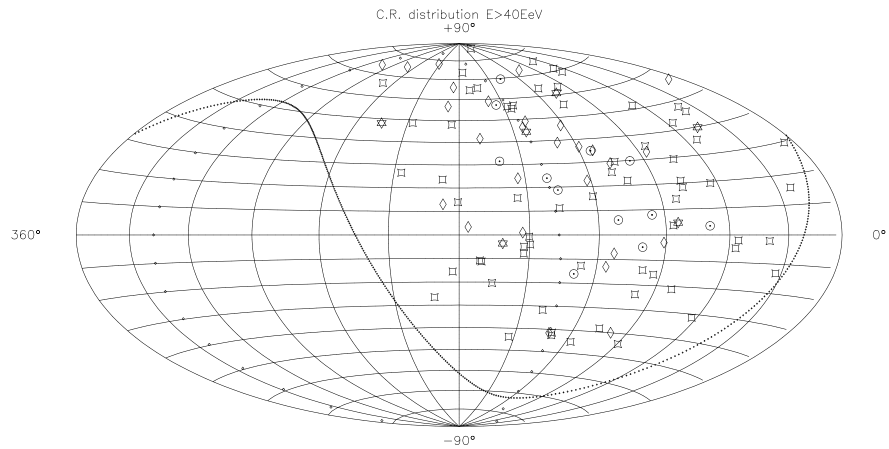

Figure 2: Arrival directions of UHECR with $E > 4 \cdot 10^{19} eV$ from four experiments [13] in Galactic coordinates. Squares - AGASA, diamonds - Haverah Park, circles - Yakutsk, stars - Volcano Ranch. Dotted line is the terrestrial equator.

Figure 3: One of the 1600 water Cherenkov detectors (the surface array), spaced by $1.5\,km$ over area of $3000\,km^2$. The solar panel and the communication antenna is seen. At the horizon a fluorescence detector on a hill can be seen.

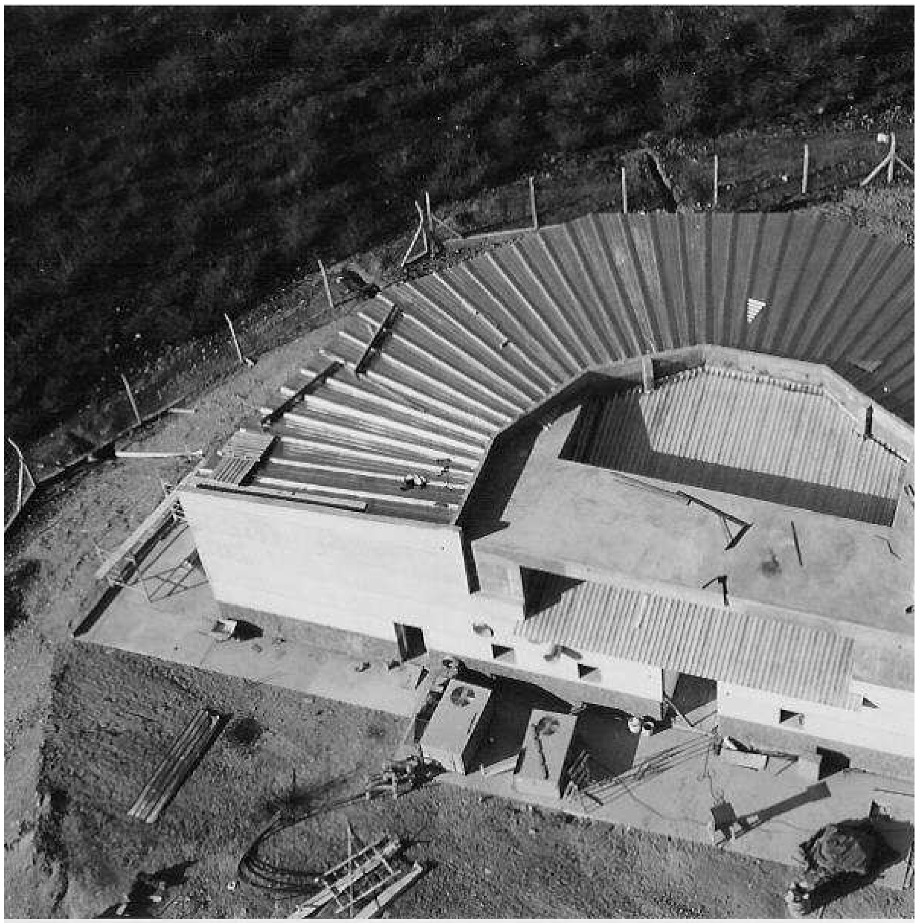

Figure 4: Top view of one of the four fluorescence detectors overlooking the surface array. It contains six telescopes , each with a field of view $30° \cdot 30°$, covering together $180°$ in azimuth (the half circle seen).

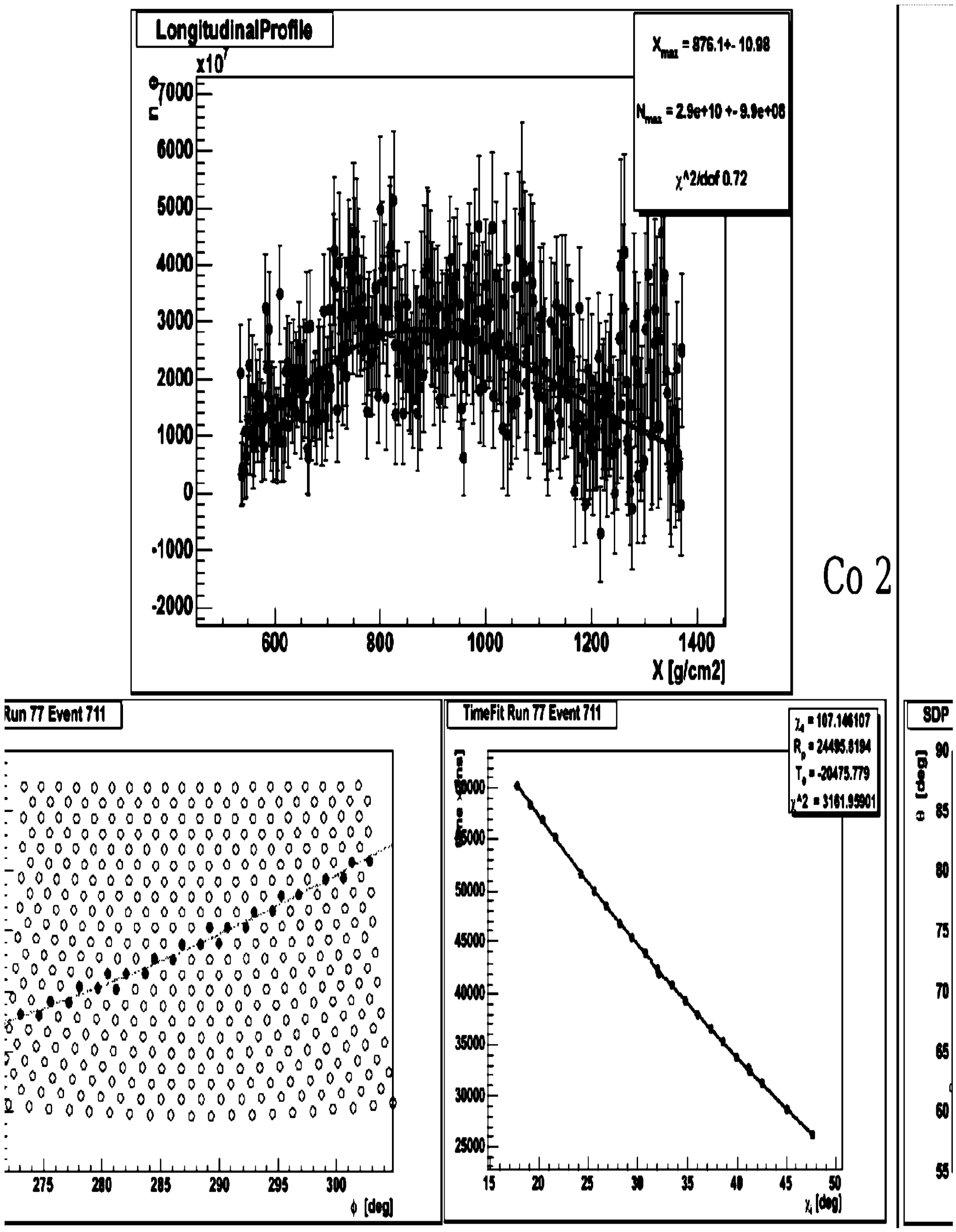

Figure 5: An example of a shower registered by a fluorescence detector (one telescope). See text for explanations.

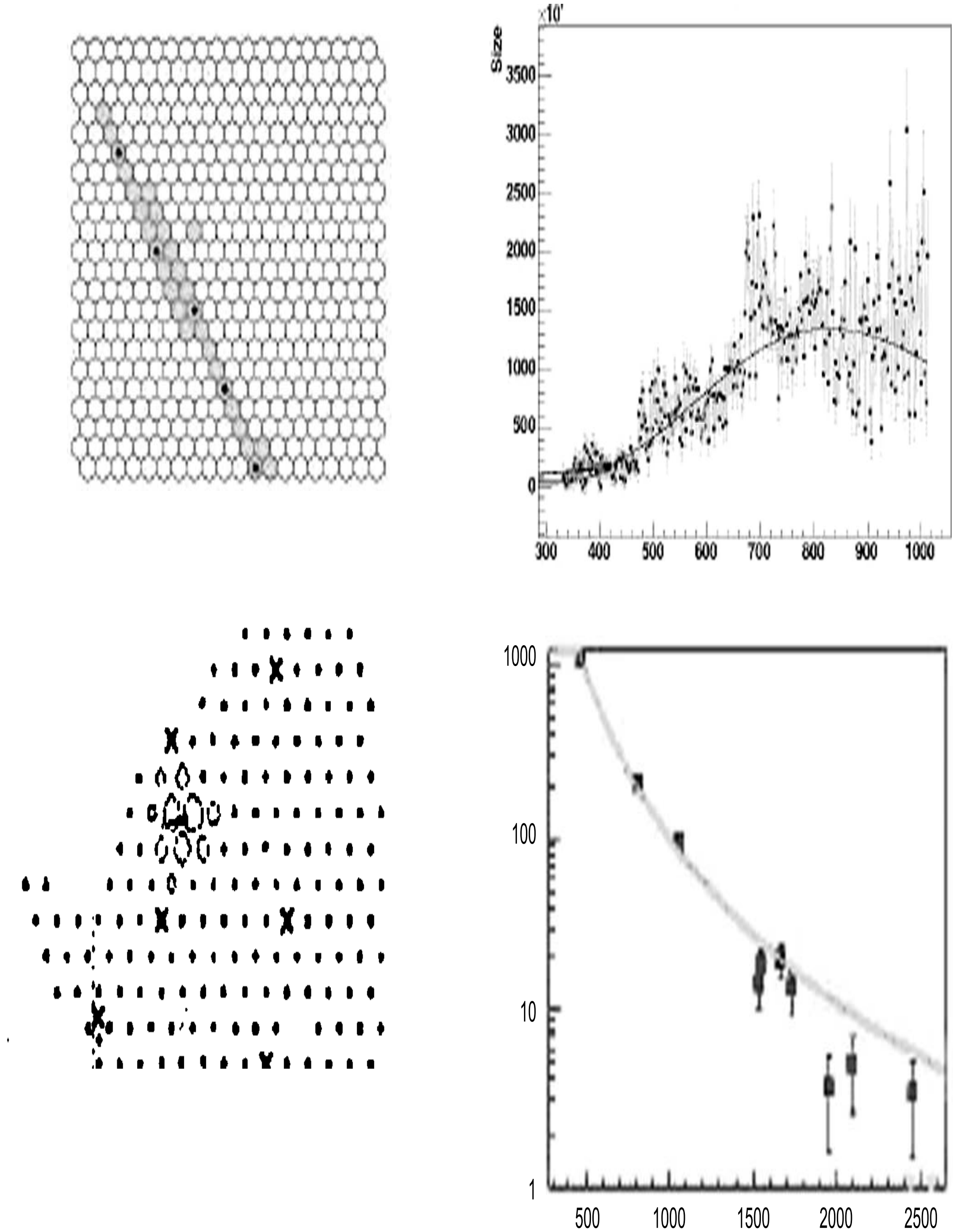

Figure 6: A hybrid shower, ie. registered by both types of detectors. In the upper right panel - reconstructed number of particles has to be multiplied by 10^7. See text.

Figure 7: A multimirror hybrid shower (seen by surface detector and two adjacent telescopes). See text for explanations