*Romanian Reports in Physics, Vol. 60, No. 1, P. 45–55, 2008*

# MINI-ARRAYS OF DETECTORS FOR THE STUDY OF COSMIC-RAY AIR SHOWERS*

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(Received August 9, 2006)

*Abstract.* Primary cosmic rays entering the Earth's atmosphere, initiate Extensive Air Showers (EAS). Mini-arrays of detectors making use of the Linsley effect measure the spread of the arrival times in particle samples and make it possible to estimate the distance to the shower axis. The potential of the mini-arrays is appraised for their use in coincidence with the electromagnetic calorimeter WILLI at NIPNE-HH Bucharest. WILLI is able to discriminate the different contributions of positive and negative muons as secondary radiation from EAS and the mini-arrays can determine different secondary particle distributions in EAS. Different experiments around the world, employing mini-arrays of detectors to study the cosmic-ray air showers are reviewed.

*Key words:* cosmic rays, extensive air showers, mini-arrays.

## 1. INTRODUCTION

The cosmic rays are charged particles coming from space. They bring on Earth information about energetic events occurring somewhere in the universe. Certain cosmic rays may exhibit amazingly high energy. The higher their energy, the lower is their flux. Up to $10^{14}$ eV, cosmic rays can be directly detected with balloon and space born experiments. Above this energy the flux is too low for the limited useful surface of the space-based detectors and cosmic rays have to be studied on the ground through the air showers they generate.

Extensive air showers (EAS) are cascades initiated by primary cosmic rays in the atmosphere. The incident particle (all range of masses from protons to iron nuclei) hits an air nucleus (mainly oxygen or nitrogen). In the first interaction, a number of secondary particles (pions $\pi^{\pm}$, $\pi^0$, kaons K, charmed particles D-mesons or $\Lambda_c$-baryons, very short living particles – resonances) are generated. Mostly by decay of the neutral pions, electromagnetic sub-cascades are initiated, and by decay of the charged pions and kaons, muons and neutrinos are produced. The charged pions may decay or they can further interact with air nuclei. A competition exists

* Paper presented at the Annual Scientific Conference, May 26, 2006, Faculty of Physics, Bucharest University, Romania.

between the two processes and which one is favored depends on the pion energy and the local air density.

The more energy a primary cosmic particle possesses, the more secondary particles will be produced and detected. In the development of the shower, the secondary particles are spread over a large area. The area increases in size with the primary cosmic ray energy. The highest energy cosmic rays create particles over an area of more than 10 $km^2$. Therefore, one cannot make a single detector of this size and it is common practice to use small detectors to measure the particle density at several locations.

As it reaches the ground the air shower is sampled by arrays of scintillators or water Cherenkov tanks. The fluorescence of the nitrogen molecules in the air can be also detected by fluorescence detectors. However, this second technique works best only in clear moonless nights and in stereo mode, when two detectors separated by many kilometers observe the same shower from two different angles and determine thus the shower axis.

The best known ground based experiments used for high energy cosmic rays studies are: KArlsruhe Shower Core and Array DEtector (KASCADE) [1], Akeno Giant Air Shower Array (AGASA) [2], High Resolution Fly's Eye (HiRes) [3] and the Pierre Auger Project [4].

KASKCADE experiment comprise of a central hadron calorimeter surrounded by a rectangular array of 252 scintillation detectors, covering an area of 40000 $m^2$. In addition there is a muon tracking detector with an effective area of 128 $m^2$. The experiment measures the hadronic, muonic and electromagnetic components of EAS in the energy range $10^{14} – 10^{17}$ eV.

AGASA covers an area of about 100 $km^2$ and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km and the detectors are sequentially connected with a pair of optical fibers. All detectors are controlled and operated by a set of commands transmitted from a central computer.

HiRes is composed of fluorescence detectors built in two different sites in the Utah dessert (USA) to be used for stereo fluorescence cosmic rays studies.

The Pierre Auger Project will consist of two giant air shower arrays one in the USA and one in Argentina (this Southern hemisphere observatory is almost completed), each with 1600 water Cherenkov detectors covering 3000 $km^2$ and four sites of fluorescence telescopes.

## 2. THE DETECTION OF THE SECONDARY MUONS IN EXTENSIVE AIR SHOWERS (EAS)

While neutrinos generated in the extensive air showers (EAS) are hardly detectable, muons might reach the observation level even from high altitudes. At sea level, the most part of the charged component of the cosmic ray showers is made of muons. They transport most of their energy fraction (though small) down to the observation level and especially survive the increased atmospheric path length in the case of the inclined (high zenith angle) events. The secondary muons in an EAS are more numerous as the energy of the primary cosmic ray and/or its mass increases.

Air showers have a lateral spread that differs for different shower components as well as for the various primary particles. The lateral distribution of the secondary muons on ground is flatter than the distribution of the secondary electrons, mostly due to the higher altitude origin of the muons. In spite of the electrons being much more numerous than muons around shower maximum, at larger distance from the shower core, the particle densities become comparable.

A larger ground electron density can be observed closer to the core for primary proton showers, while for iron generated events a larger muon density will appear closer to the core. Thus, measuring local particle densities of the different shower components as a function of core distance, one can obtain additional information about the type of the primary particle [5].

The ratio of the numbers of positive to negative muons in an EAS is called the muon charge ratio. It provides information on the interactions of the primary cosmic rays with the atmosphere nuclei, since it reveals detailed features of the multiplicity distributions and production cross sections of the parent particles.

The propagation of the primary cosmic rays and of the secondary shower particles is noticeably influenced by the Earth's magnetic field and eventually by solar modulations. Thus additionally to the particle physics aspects there are further perspectives of muon charge ratio studies. The muon charge ratio may be also a sensitive test quantity of hadronic interaction models.

As a consequence of the importance that the secondary muons exhibit for the cosmic ray studies, a sampling calorimeter, **WILLI (Weakly Ionising Lepton Lead Interactions)** (Fig. 1), was built up in NIPNE Bucharest for prototype studies of muon interactions with the matter [6]. WILLI was designed in context with the air shower experiment KASCADE and it is a compact device for performing measurements of the charge ratio of cosmic secondary muons by detecting the life time of the muonic atoms.

In the first stage of realization, the detector consisted of 20 layers of lead (1 cm thickness), separated by 20 active layers of NE114 scintillators (3 cm thickness) placed in between aluminum layers (1.2 cm thickness), being used for both exploratory studies of muon energy spectroscopy and for muon charge ratio measurements. In a subsequent configuration (1998) the detector has been optimized for muon charge ratio measurements, by removing the Pb layers and improving the geometrical set-up and background rejection by use of anticounters. WILLI is now operational into a configuration for the observation of muons with different angles of incidence in zenithal and azimuthal plane.

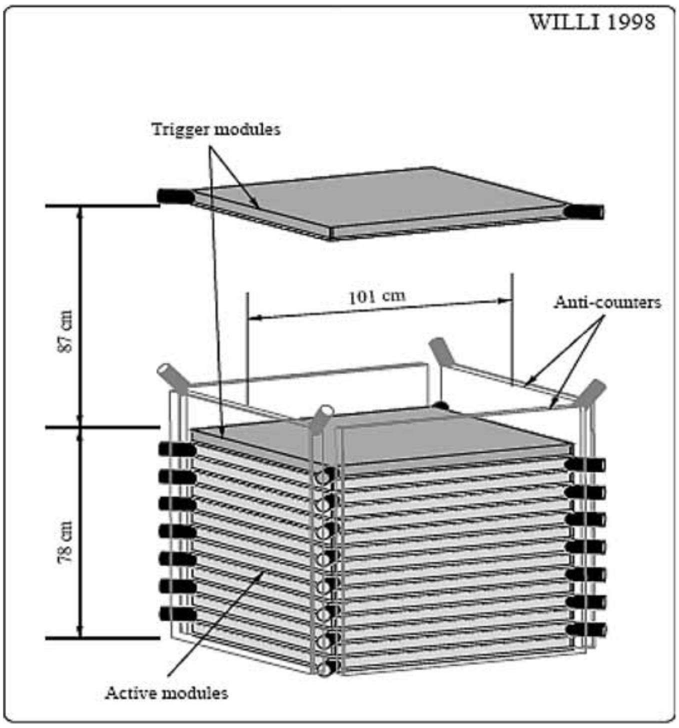


Fig. 1 – Schematic view of the WILLI detector at NIPNE Bucharest.

The principle of the measurement is based on the different behavior of positive and negative muons in matter. Stopped positive muons decay by the lifetime of free muons. Negative muons are captured in atomic orbits, where they may decay or are absorbed by the atomic nucleus. This leads to a reduced life time of stopped negative muons, depending on the stopping material. Aluminum reduces significantly the effective mean life time of negative muons as compared to that of the free decay of positive muons.

WILLI is going to be extended with a small array of detectors for determination of EAS core location, direction and arrival time. The number of systems in the mini array, the distance between each system and the distance from the mini array and WILLI will be determined after careful simulations performed with GEANT4 and CORSIKA.

## 3. MINI-ARRAYS OPERATING INDEPENDENTLY OF EACH OTHER FOR THE STUDY OF HIGH ENERGY COSMIC RAYS

The main difficulty in studying the highest energy cosmic rays is their extremely low intensity. Instead of gathering all the available resources in one place (ex. AGASA, HiRes, Pierre Auger, KASCADE), John Linsley suggested [7] a way to solve the problem at much less cost per unit sensitive area: the use of numerous inexpensive mini arrays operating independently of each other and having small dimensions compared with the distances to the axes of studied showers. They can operate anywhere, even in the cities and in addition to the quantities usually observed each mini array will record shower particle arrival time distributions.

The secondary particles in an EAS form a pancake moving at the speed of light towards the earth in the direction of the primary particle. This pancake will hit the earth at different times when it is not exactly parallel to the earth' surface. The Linsley effect is the increase in spread of arrival times in a particle sample from a given shower with increasing distance from the shower center. Thus, the measured time spread of particles striking a localized detector system can give the distance to the shower axis [8].

It is well known that the longitudinal thickness of the particle swarm in an EAS, increases rapidly with increasing distance from the shower axis (Fig. 2). It is 1 ÷ 2 m at $r < 10$ m and it goes to hundreds of meters at $r > 1$ km [9].

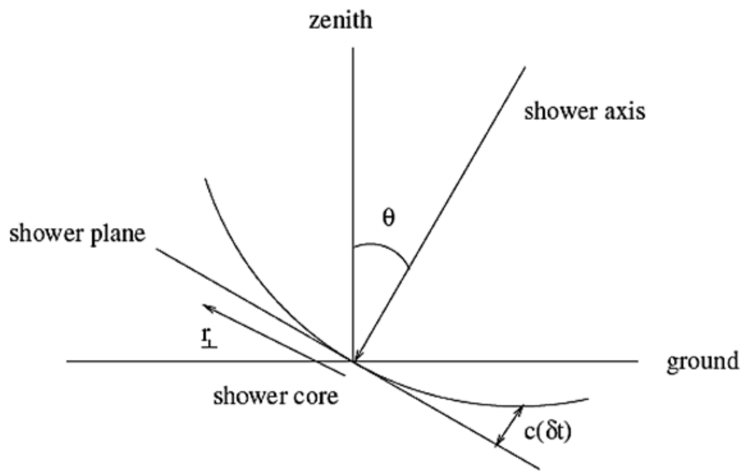


Fig. 2 – Geometrical parameters of an extended air shower (EAS) [9]; $r_\perp$ is the distance from the shower axis to the measurement point and δt is the time delay.

In the empirical formula $\sigma_{time} = 2.6 \cdot \left(1 + \frac{r}{30}\right)^b$, $\sigma_{time}$ is the time dispersion (ns), $r$ is the distance to the shower axis ($m$) and $b = 1.5$ is an empirical parameter [7]. With it one can determine r from measurements of $\sigma_{time}$. The accuracy on the determination of $r$ depends on the energy and mass of the primary cosmic ray, the zenith angle and the starting depth of the shower.

The purpose of the mini arrays is to scan the largest possible area consistent with a given uncertainty. The center of the EAS should fall up to a maximum distance determined by the minimum detected particle number that gives a tolerably small uncertainty. This number was determined to be 8–10 for an uncertainty in shower size of ~ 30% [8]. The events involved make the multiparticle hits on a detector, unlikely, which means the detectors are effectively single-particle counters.

A guide for designing mini-arrays used to exploit the Linsley effect in the study of EAS must also include the calculation of the expected rates. The results are a useful tool for choosing the detectors and their placement. Detailed calculations are given in [10] and the conclusion states that it is necessary to go down to low particle densities (large detection areas), in order to get a good rate for high energy showers (a big number of particles spread over a large area). However, a too low particle density would also imply a large amount of statistical fluctuations and a larger accidental rate. Therefore a tradeoff must be reached.

The hardware trigger should be carefully designed so that a minimum value of the time spread is imposed. This reduces triggers by showers with centers striking near the detection cluster (too small time spread). The triggers from small showers (low energy) are also eliminated by the requirement that a minimum particle number should be generated in the detectors.

A number of experiments around the world using mini-arrays of detectors for the high energy cosmic ray studies will be reviewed and their characteristics summarized in the next section.

## 4. MINI-ARRAY EXPERIMENTS FOR THE STUDY OF HIGH ENERGY COSMIC RAYS

### 4.1. CHICOS EXPERIMENT

CHICOS (California HIgh school Cosmic ray ObServatory) [9, 11, 12] is an array of more than 140 detectors distributed over a large area (400 km$^2$) of southern California, and will consist of 180 detectors at 90 locations in the near future. These sites, located at area schools, are equipped with computerized data acquisition and the automatic data is transferred nightly (via internet) to Caltech lab. The goal of CHICOS is to provide data related to the flux and distribution of arrival directions for ultra-high energy cosmic rays.

When a series of individual detector hits passes cuts and it is considered a candidate shower event, the measured densities are used to determine the location and energy of the primary cosmic ray. The time of hits in each detector is used to determine the primary direction. To properly reconstruct the arrival direction, it is necessary to know the shape of the shower front. Furthermore, the direction and energy are correlated since a more inclined shower must traverse a greater atmospheric slant depth resulting in an older shower. Since CHICOS is sited at an atmospheric depth well beyond shower maximum, inclined showers are attenuated relative to vertical showers.

### 4.2. HISPARC EXPERIMENT

HiSPARC (High School Project on Astro-Physics Research with Cosmics) [13, 14] is a national Dutch initiative, which aims to build a large national network of cosmic ray detectors on high schools. On one hand HiSPARC creates enthusiasm within high school students and teachers for the exact sciences by allowing them to participate in a scientific experiment. On the other hand HiSPARC is a scientific experiment, investigating cosmic rays at energies between $10^{16}$ and $10^{19.5}$ eV. The cosmic ray detector is organized in clusters, with typical distances between clusters of about 50 km. This allows a search for long range correlations and would even allow for particle-interferometry in case correlations are found. Each of the clusters consists of an array of particle detectors and is centered on a scientific institute which provides the local organization and support.

### 4.3. ALTA EXPERIMENT

ALTA (Alberta Large-area Time-coincidence Array) [15, 16] project initiated in 1996, is a collaboration between the University of Alberta and a number of high schools and colleges to deploy a very large area (~ 100,000 km$^2$) sparse cosmic ray air shower array across Alberta in Canada. The main research aim of the ALTA collaboration is to search for non-random components of EAS phenomena as evidenced by very large area time coincidences.

The ALTA array currently consists of eleven independent detector stations. Additional four detector systems are under construction with eight additional detector systems under consideration. The local detector systems consist of a triplet of scintillator detectors, each with a sensitive area of 0.5 m$^2$, laid out at the vertex of an equilateral triangle with side 10 m long. An incoming shower of large enough extent, impinging on the local detector triplet, will cause a local coincidence between the detectors forming the triplet.

### 4.4. ROLAND MAZE PROJECT

In the proposed experiment [17], the detection points are placed on the roofs of Lodz high schools (Poland). Their net is dense enough to enable observation of particles starting from energies of $10^{18}$ eV. While the large experiments are dedicated exclusively to the important scientific issues, in this project each station (school) constitutes an autonomous air shower array. For the available spacing between the detectors in a station (of the order of ~10 m) the chance of observing highest energy showers in one separate station is very small, but a special trigger system provides full efficiency of registration of showers with energies ~ $10^{15}$ eV falling on the detection area (100 $m^2$).

To enable independent observations in a separate station (high school) each of them should be equipped with 4 scintillation counters of area ~ 1 $m^2$. In order to coordinate the work of all the stations, which is the essence of the described project, the GPS system is used for time synchronization.

### 4.5. LAAS EXPERIMENT

The LAAS (Large Area Air Shower) experiment [18, 19] has deployed eleven EAS arrays in large part of Japan, in order to find intensity correlations of ultra high energy cosmic rays. Searches for pairs or groups of coincident and parallel EAS observed by stations separated by 1–900 km were performed. Possible sources for such events include very short bursts of active stars, $\gamma$-ray bursts and decay products from EHE cosmic rays (the Gerasimova-Zatsepin effect). In this latter effect a high energy atomic nucleus approaching the earth dissociates on an optical photon from the sun. The two or more nuclear fragments can reach the earth at distant locations at almost the same time.

Since 2002, four EAS arrays have been operated in Okayama area as part of LAAS experiments in coincidence with a muon spectrometer (baselines in the range 100 m to 1 km) [21]. The purposes of these arrays are to study the cosmic ray energy spectrum, anisotropy in arrival direction and multiple EAS events.

### 4.6. SCROD EXPERIMENT

Each detector of SCROD (School Cosmic Ray Outreach Detector) [22] is constructed from a set of plastic scintillators. Cosmic rays are time stamped using GPS devices and the data is forwarded to the central site at Northeastern University (Boston, USA). A special technological feature of the SCROD project is the use of Avalanche Photodiodes (APD's) to collect the light produced in the scintillators and generate the electrical signals. APD's are photodiodes where a large internal electric field enables electrons to gain enough energy within the device to free more electrons in the semiconductor [23]. They have high quantum efficiencies, exceeding those of the traditional photomultiplier tubes. APD's are also mechanically robust and easy to use.

The main research goal of SCROD is the search for long-range correlations among air showers occurring at very large separations. Several processes are expected to give rise to very long-range correlations. In addition to the phenomena already mentioned in subsection 4.5, it must be mentioned that highly energetic dust grains could also dissociate and give rise to widely-separated showers [24].

The primary background for genuine long-range correlations arises from random coincidences of low energy showers. At SCROD this is controlled by detector spacing and eventually by pulse-height analysis of the scintillators signals.

The basic technical parameters of the projects described in Sections 4.1–4.6 are summarized in Tables 1 and 2.

*Table 1*

Basic technical parameters of some mini-array experiments around the world (Part 1)

| Experiment | Number of Stations | Distance between Stations | Total Detection Area | Energy Range | Altitude above Sea Level | Maximum Zenith Angle | Simulations Package Used |
|---|---|---|---|---|---|---|---|
| **HiSPARC** | 35 in 5 clusters | 1.3 km and 50 km between clusters of stations | 100 km$^2$ in the future | $10^{16}$ – $10^{19.5}$ eV | not available | not available | CORSIKA |
| **CHICOS** | 70 at present 90 final | 2–3 km | 400 km$^2$ in the future | ~ $10^{14}$ eV or $10^{18}$–$10^{21}$ eV | 250 m | 50° | AIRES |
| **ALTA** | 13 at present | not available | 100000 km$^2$ | more than $10^{14}$ eV | not available | not available | CORSIKA |
| **Roland Maze** | 2–4 | 0.5–2 km | not available | ~ $10^{15}$ eV or $10^{18}$–$10^{20}$ eV | not available | not available | not available |
| **LAAS/ Okayama** | 11 | 10–1000 km LAAS, 500–1000 m Okayama | 130000 km$^2$ | ~ $10^{15}$ eV or $10^{16}$–$10^{18}$ eV | ~ 50 m | 45° | CORSIKA |
| **SCROD** | not available | 1 km | not available | ~ $10^{15}$ eV or $10^{17}$–$10^{19}$ eV | ~ 50 m | not available | not available |

*Table 2*

Basic technical parameters of some mini-array experiments around the world (Part 2)

| Experiment | Number of Detectors per Station | Distance between Detectors | Type of Detectors | Width of the Scintillator Slab | Area of the Scintillator Slab | Number of Photomultiplier Tubes per Scin-tillator Slab | Trigger Rate |
|---|---|---|---|---|---|---|---|
| **HiSPARC** | 2 | 2–3 m | scintillator | 2 cm | 0.5 m$^2$ | 1 | not available |
| **CHICOS** | 2 | 3 m | plastic scintillator | 5–10 cm | 1 m$^2$ | 1 | 1000 events/day/site at $10^{14}$ eV 1 event/month/2 sites at $10^{18}$ eV |

(continues)

*Table 2* (continued)

| **Experiment** | **Number of Detectors per Station** | **Distance between Detectors** | **Type of Detectors** | **Width of the Scintillator Slab** | **Area of the Scintillator Slab** | **Number of Photomultiplier Tubes per Scintillator Slab** | **Trigger Rate** |
|---|---|---|---|---|---|---|---|
| **ALTA** | 3 | 10 m | plastic scintillator | 1 cm | 0.36 $m^2$ | 1 | 3800 events/day/station at $10^{14}$ eV |
| **Roland Maze** | 4 | 10 m | scintillator | not available | 1 $m^2$ | not available | not available |
| **LAAS** | 5–8 | 15 m | plastic scintillator | 5 cm | 0.25 $m^2$ | 1 | 1400 ÷ 4600 events/day/station at $10^{14}$ eV<br>2 events/83 days/4 Okayama stations |
| **SCROD** | 4 | not available | plastic scintillator | not available | Not available | One Avalanche Photodiode instead of PMTs | not available |

## 5. CONCLUSIONS

Mini-arrays of detectors that utilize the Linsley effect may provide a simple and less expensive method, albeit more limited in its capability, of performing high energy cosmic ray studies. The distance between the locations where the particle density and arrival times are recorded depends on the altitude (sea-level) and energies of interest. This matches sometimes, the distance between high-schools in an urban area rather well and therefore this measurement is a natural candidate for a successful collaboration between high-schools and scientific institutes. The educational as well as the scientific potential of the studies involving mini-arrays is therefore very high. A mini-array of scintillation detectors read-out by photomultiplier tubes is going to be built at NIPNE Bucharest for high energy cosmic ray studies. The data provided by the mini-array will be compared with the data provided by the WILLI detector already in operation at NIPNE Bucharest.

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