Astrophys. Space Sci. Trans., 7, 307–310, 2011
www.astrophys-space-sci-trans.net/7/307/2011/
doi:10.5194/astra-7-307-2011

Astrophysics and **S**pace Sciences
Trans**a**ctions

Developments in shower reconstruction and composition analysis for CARPET-3 EAS array

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Received: 14 November 2010 – Revised: 15 April 2011 – Accepted: 25 April 2011 – Published: 31 August 2011

Abstract. This contribution describes the current progress on the composition analysis of data recorded with Carpet EAS detector. The focus of the paper is on the methodological side of analysis.

1 Introduction

A study of the primary composition in the PeV region can currently be carried out solely by means of extensive air shower (EAS) measurements. These measurements rely on the use of different particle interaction models describing the development of EAS in the atmosphere and indicate that the mass composition of primary spectrum change in the PeV region, as reviewed and discussed by Blümer et al. (2009). As direct experiments measuring the primary particle spectrum at and above the PeV region are not in the foreseeable future, further ground based observations on the properties of EAS with different detection and analysis techniques are needed.

Precision measurements of the lateral density functions (LDFs) of charged particles in EAS have been performed with the Carpet EAS array. This measurement can give further light on the composition of the primary cosmic-ray particles in the knee region.

This contribution focuses on some of the aspects relevant to the development of the new methods of analysis of the Carpet EAS data. The experimental LDFs, compared with simulated ones (CORSIKA QGSJET 01C, Heck et al., 1998), are presented and further description is given on the progress of the development of analysis methods. Such developments are needed for analysis of new data and for analysis of the newly proposed Carpet-3 EAS array.

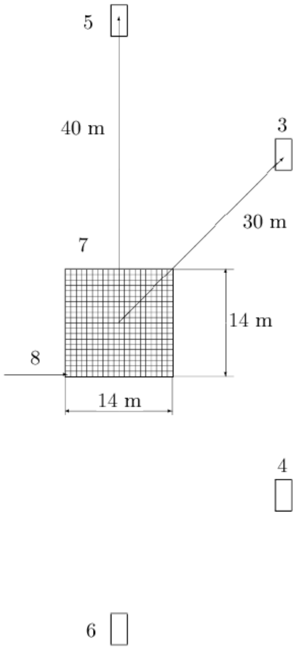

Fig. 1. Carpet EAS array. 1 – 6 - remote stations; 7 - Carpet; 8 - individual scintillation detector ($0.71 \times 0.71\,\mathrm{m}^2$).

2 CARPET EAS array

Baksan Neutrino Observatory INR RAS hosts the “Carpet” EAS array at the altitude of 1700 m a.s.l (atmospheric depth 840 $\mathrm{g/cm}^2$, 43.28° N, 42.69° E). The parts of the array (see Fig. 1) used in this study consists of a Central detector (400 individual scintillation detectors 0.5 m^2 each) and six outer stations (18 scintillator detectors in each). A more detailed description of the detector is given elsewhere (see Dzhappuev et al., 2007, and references therein).

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Published by Copernicus Publications on behalf of the Arbeitsgemeinschaft Extraterrestrische Forschung e.V.

Table 1. The simulation statistics for proton-initiated CORSIKA air showers used in the study of average LDFs. The simulation energy interval was divided into six intervals. N_k denotes the number of simulated showers for each interval, w_k denotes the spectral weight, and n_{1k}, n_{2k} and n_{3k} are the yields for each shower size interval $N_e \in (1.5-2.0)\cdot 10^5$, $N_e \geq 2.0\cdot 10^5$ and $N_e \geq 8.0\cdot 10^5$.

k	Energy PeV	N_k	w_k	n_{1k}	n_{2k}	n_{3k}
1	$0.237-0.316$	1600	0.73439	30	5	0
2	$0.316-1.00$	1750	1.00000	127	116	0
3	$1.00-3.16$	1350	0.14102	197	936	88
4	$3.16-10.0$	420	0.01995	0	420	300
5	$10.0-31.6$	95	0.00281	0	95	95
6	$31.6-100.0$	20	0.00040	0	20	20

The proposed extension of the array, Carpet-3 EAS array, Szabelski et al. (2009), is a multipurpose array, studying the EAS with at least six parameters.

3 A study on lateral density density distributions

The average LDFs have been measured, Petkov et al. (2009), for three shower size intervals: $N_e \in (1.5-2.0)\cdot 10^5$, $N_e \geq 2.0\cdot 10^5$ and $N_e \geq 8.0\cdot 10^5$. Data were taken in the past (year 1976) with total live time of 1800 h. Air showers with reconstructed axes inside the central detector of Carpet and with reconstructed zenith angles $< 30°$ were selected for analysis. In total this data set consists of 831 recorded showers (166, 665 and 100 in respective shower size bins).

The shower sizes of these showers were reconstructed by fitting the NKG-function to the measured densities over the distance range of $20-50$ m. The NKG-function reads

$$f_{NKG}(r;N_e,s) = (N_e/R_M^2)\times(r/R_M)^{(s-2)} \times(1+r/R_M)^{(s-4.5)}\times C(s), \quad (1)$$

where N_e is the reconstructed shower size (total number of charged particles in the shower), s is the shower age (here $s = 1.0$ was fixed), R_M is the Moliere radius (here $R_M = 94$ m), r is the distance from shower axis and

$$C(s) = \Gamma(4.5-s)/(2\pi\Gamma(4.5-2s)\Gamma(s)) \quad (2)$$

is a normalization factor. The measured particle densities have been corrected for transition effects originating as the shower particles propagate through the roof of the detector hall and in the scintillators. The shower axis positions of air showers were taken to be the coordinates of the detector with the highest recorded particle density. A study has been made in order to compare the measured LDFs with a CORSIKA simulation expectation.

Table 2. The simulation statistics for iron-initiated CORSIKA air showers. See Caption of Table 1.

k	Energy PeV	N_k	w_k	n_{1k}	n_{2k}	n_{3k}
2	$0.316-1.00$	2000	1.00000	0	0	0
3	$1.00-3.16$	2000	0.14102	243	287	0
4	$3.16-10.0$	600	0.01995	9	588	118
5	$10.0-31.6$	100	0.00281	0	100	99
6	$31.6-100.0$	20	0.00040	0	20	20

The development of EAS in the Earth atmosphere has been simulated with the CORSIKA-package. QGSJET01C and GHEISHA2002d were used as the high and low energy hadronic interaction models. The low energy limit of particle tracking was set to 1 MeV for electromagnetic particles and 50 MeV for hadrons and muons. The multiprocessor computers 'Kuusi1' and 'Kuusi2' of the University of Oulu were used to execute the time-consuming simulations.

The simulations have been done for primary protons and iron nuclei. The shower arrival angles were distributed taking into account the isotropy of the primary flux and a flat detector geometry ($dN \sim \sin\theta\cos\theta d\theta$) in the range of $0-30°$. The simulation energy range was from 0.2 to 100 PeV corresponding to the N_e-range of measurements. The spectral index -2.7 was used and due to steeply falling spectrum the simulations were divided into several primary energy intervals. The simulation statistics are given in Tables 1 and 2. It was estimated that air showers with energies below the lower energy limit can contribute $< 0.3\%$ to the number of showers in the lowest shower size interval. The expected number of EAS with energies above the upper energy limit is < 1.

In this exercise, the average LDFs were reconstructed as follows. First, the simulated shower particle densities were tabulated in the shower plane. Second, the shower size was estimated by fitting the NKG-function to particle densities in the distance range of $20-50$ m. The shower axis was at a fixed location and the uncertainties of shower direction and shower axis reconstruction were assumed to be negligible. As with measurements, $s = 1.0$ and $R_M = 94$ m were used as the parameters of the NKG-function. Such a simplification (namely keeping $s = 1.0$ fixed) in shower size estimation (see Chapter 4) can be done. Third, the average LDF for each shower size interval, $\overline{\rho}_j(r)$, was constructed as the weighted average of individual shower densities contributing to the shower size interval, namely by

$$\overline{\rho}_j(r) = \frac{\Sigma_k W_{jk}\times\frac{1}{n_{jk}}\Sigma_{i=1}^{n_{jk}}\rho_{ijk}}{\Sigma_k W_{jk}} \quad (3)$$

where $\rho_{ijk}(r)$ is the particle density of shower i, in shower size interval j, and energy interval k; n_{jk} the number of showers contributing to shower size interval j from energy

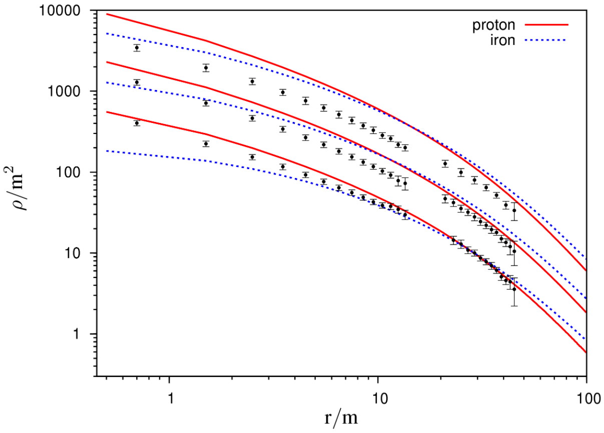

Fig. 2. The average lateral density distribution of charged particles compared with simulation results. Data are shown (points with error bars) for three different shower size intervals. The errors are statistical only. Lines below - $N_e \in (1.5-2.0)\cdot 10^5$, lines in the middle - $N_e \geq 2.0\cdot 10^5$, and lines on top - $N_e \geq 8.0\cdot 10^5$. Red lines - pure proton spectrum, Blue dashed lines - pure iron spectrum; Spectral index $\gamma = -2.7$.

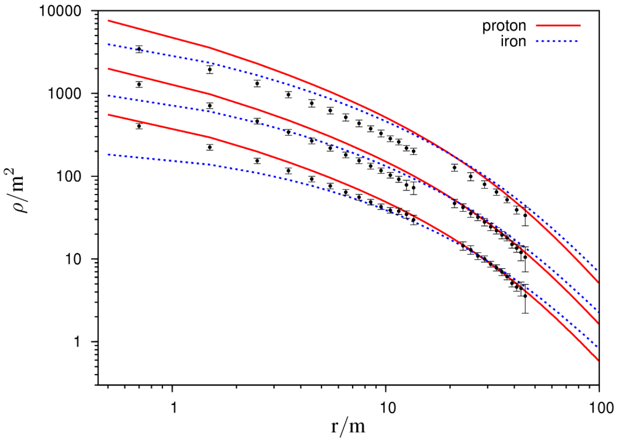

Fig. 3. The average lateral density distribution of charged particles compared with simulation results. See caption of Fig. 2. Here spectral index was $\gamma = -2.7$ for $E < 3$ PeV and $\gamma = -3.1$ for $E \geq 3$ PeV.

interval k and $W_{jk} = w_k * n_{jk}/N_k$ is a weight which takes into account both the steeply falling energy spectrum and shower size distributions. To generate spectral index -3.1, reweighting of shower particle densities with energy dependent factor ($\sim E^{2.7}/E^{3.1}$) was used.

The results of these simulations are compared with measurements in Figs. 2 and 3. The simulated proton curve follows close by the data points in the case of the lowest shower size interval. However, for the higher shower size intervals, the simulation results deviate from the data. This may be due to several systematical effects, not taken into account in the study. The shower reconstruction has been done in a simplified scenario and the uncertainties of shower axis reconstruction are not incorporated in the simulated LDFs (see Chapter 4). This may lead to an overestimate of the simulated curve compared with the measured one at short distances. Also the transition effects, which were taken into account only on the average (not shower by shower), may have an effect on the shower fluctuations. On the other hand, the simulation result of average LDFs is also model dependent, as presented by Heck (2008). Therefore a new data set with FLUKA as the low energy model has been simulated. Further simulation options include the use of EPOS as the high-energy interaction model. Thereafter we continue analysis with studies on the model dependence and with light-heavy composition mixtures.

4 Studies on the shower reconstruction methods

Apart from the study of lateral density distributions, focus has also been on the development of new shower reconstruction methods. For the analysis of the cosmic-ray composition there is a need to accommodate more aspects of detector responses into the simulation procedures. Development of the procedures includes studies on different fit methods, the array geometry, uncertainties in the reconstruction of the shower arrival direction and shower axis position as well as Monte Carlo generator for the detector response. These aspects can be studied with CORSIKA air showers and specially developed tools.

We have studied different methods to estimate shower sizes. CORSIKA air showers, with a given energy and shower size (N_e^{true}), were simulated and the shower size of the simulated shower was reconstructed (N_e^{rec}) with different methods. Usually the methods rely on the minimization of the quantity $\chi^2 = \Sigma_{r=r_{min}}^{r_{max}} w(r) \times (\rho(r) - f_{NKG}(r;N_e,s))^2$, where $\rho(r)$ are the particle densities, $w(r)$ an associated weight, and r_{min} and r_{max} denote the lower and upper limits of the fit range. The shower age s can be either a free variable or fixed to a value ($s = 1.0$), the range of the fit can be varied ($20-50$ m or $0-50$ m) and the weight can be assigned differently ($w(r) = 1/f_{NKG}(r;N_e,s)$ or $w(r) = 1$). Also, instead of minimizing the χ^2-value, the shower can be reconstructed by maximizing a log-likelihood function $\mathcal{L}^*(N_e,s) = \sum_{r=r_{min}}^{r_{max}} \log P(\rho(r)|f_{NKG}(r;N_e,s))$ where $P(N|\mu) = \frac{\mu^N \times e^{-\mu}}{N!}$ is a Poisson probability. A few examples of the relative residuals of the different shower size estimations are shown in Fig. 4. The biased estimator used in the study described in Sect. 3 (method 7 in Fig. 4) was chosen due to lack of computing power in the past. More refined methods (such as method 1 or 3) give better estimates and are thus planned to be used for analysis of new data.

In another study, a realistic array geometry was implemented into the shower simulations codes and the accuracy of shower axis reconstruction was studied. The shower axis position was set to a given value ($\overline{x}^{true}$) in the simulations

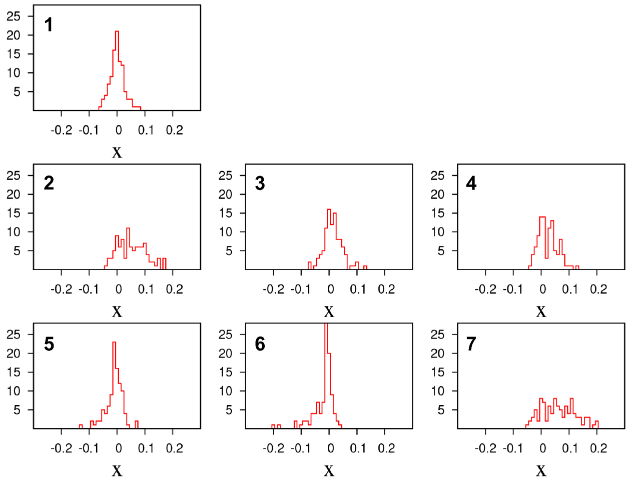

Fig. 4. Example of $X = \frac{N_e^{true}-N_e^{rec}}{N_e^{true}}$-distributions for simulated 1 PeV proton showers. Seven shower size reconstruction methods are compared (indicated by a label in the upper left corner of each spectrum). 1 - maximum log likelihood fit, range $0-50$ m, 2 - $w(r) = 1/f_{NKG}(r)$, $20-50$ m, $s = 1.0$, 3 - $w(r) = 1$, $20-50$ m, s free, 4 - $w(r) = 1/f_{NKG}(r)$, $20-50$ m, s free, 5 - $w(r) = 1$, $0-50$ m, s free, 6 - $w(r) = 1/f_{NKG}(r)$, $0-50$ m, s free, 7 - $w(r) = 1$, $20-50$ m, $s = 1.0$ fixed.

and the coordinates were reconstructed ($\overline{x}^{rec}$) in different ways. A comparison of two methods is shown in Fig. 5. The methods are: (1) shower axis is defined as the coordinates of a detector with the highest particle density, and (2) the axis position is defined as the coordinates resulting from a fit of the NKG-function, when shower axis position ($\overline{x}^{rec}$), shower age (s) and size (N_e) are free. According to this simulation study, the shower axis determination accuracy (the average difference between the reconstructed shower axis position and the true axis position on the shower plane) of Carpet EAS array is ~ 0.25 m at its best and is similar for both methods. For low energy showers (~ 1 PeV), the accuracy is significantly worse and depends on the used method.

5 Conclusions

The data recorded by Carpet EAS array can be analyzed for the composition of primary cosmic ray particles in the knee region.

A study on the lateral density distributions of charged particles recorded with the array was made. This study will continue with model comparisons and composition mixture analysis.

Development has been made on the methods of shower reconstruction for the Carpet EAS array. These are studied and developed with simulation tools using CORSIKA air showers - we will look for these method implementations for the upcoming analysis on newly recorded data of Carpet or further Carpet-3 experiment.

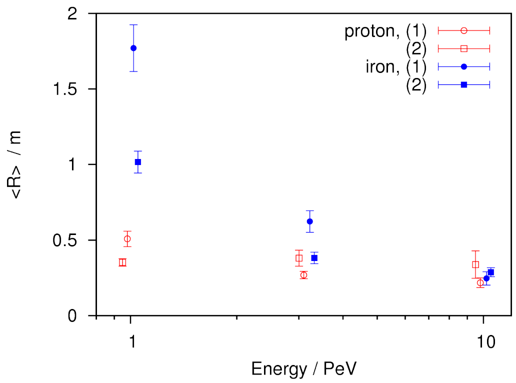

Fig. 5. Simulation results of shower axis reconstruction accuracy for different energies and primary masses. Average shower axis reconstruction accuracies $(< R >= \Sigma_{i=1}^{N}|\overline{x}^{rec} - \overline{x}^{true}|/N)$ with the standard errors are shown for energies 1.0 PeV, 3.16 PeV and 10.0 PeV and for proton (red, open symbols) and iron (blue, filled symbols). $\overline{x}^{true}$ was distributed uniformly around the center [in area of 0.71 m × 0.71 m] of the central detector. Results of two methods are shown: (1) method of maximum density (circles) and (2) NKG-function fit (squares). The symbols have been slightly shifted in horizontal direction for clarity.

Acknowledgements. This work is carried out in the frame of Agreement for Scientific cooperation in the Field of Astroparticle Physics between Institute for Nuclear Research of RAS (Russia) and Department of Physics, University of Jyvaskyla (Finland). The work of Russian scientists was supported by the 'Neutrino Physics and Astrophysics' Program of the Russian Academy of Sciences. DDD and NFK acknowledge the support of RFBR (grant 10-02-00735). JS thanks the support of Oulu University Scholarship Foundation.

Edited by: K.-H. Kampert
Reviewed by: two anonymous referees

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