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Direction distributions of air showers observed with the Turku air shower array

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Abstract. The Turku air shower experiment is briefly described and the shower analysis is outlined giving emphasis on the timing properties. The arrival direction distributions and the pointing accuracy of the array are determined and discussed.

1 Introduction

Cosmic rays with energies $> 10^{13} - 10^{14}$ eV arrive at Earth uniformly distributed both in time and direction. This is because they, being charged particles, suffer multiple deflections in the random magnetic fields along their paths. The solar activity can not affect their motion, and the interplanetary magnetic fields are not strong enough to deflect them. Therefore these local phenomena cannot produce asymmetry in the direction distribution of these high-energy particles.

Directional asymmetry of cosmic rays could, however, be expected for two reasons (Greisen, 1960). Firstly, the higher the energy of a cosmic ray, the less it suffers deflections along its track and the more precisely its arrival direction points back to its origin. Secondly, the non-uniformity of the galactic structures should produce asymmetric diffusing and leakage processes of cosmic rays, and this would lead to anisotropy in the arrival directions of cosmic rays. The observed directional isotropy is thus not easily explained.

There are also indications (Ciampa and Clay, 1988) that the shape of the zenith angle distribution of air showers is sensitive to the spectral index and composition of primary particles.

The directional isotropy and direction distributions of primary cosmic radiation therefore continue to be interesting, as the fundamental questions about the sources and acceleration mechanisms of high-energy cosmic rays remain unsolved.

Sources or sinks of primary cosmic rays may be discovered only after carefully linking the arrival direction of an air shower with its occurrence time to yield the arrival direction in celestial co-ordinates. This necessitates a large number of air shower data with excellent timing qualities, as the sources or sinks may manifest themselves only as tiny excesses or deficits of events in certain directions against the background of uniformly distributed bulk of primary cosmic rays. –Here a 'sink of cosmic rays' signifies a massive heavenly body, such as the Sun or the Moon, relatively close to Earth, absorbing primary cosmic rays and thus shadowing the solid angles they cover as seen from the Earth.

In this paper we determine the arrival direction distributions of the air showers detected with the air shower array in Turku. In the following we first describe the experimental set-up, the analysis procedure and the shower selection criteria. In Sect. 3 we shall analyse our data and finally in Sect. 4 we discuss and compare our results with previous ones.

2 Air shower experiment in Turku

The Turku air shower array consisted of scintillation detectors installed symmetrically covering a circle with a radius of about 11 metres. A diagram showing the locations of the detectors is shown in Fig. 1. The array and the air shower measurement system are described in more detail in e.g. Elo et al. (1990, 1993) and Elo and Arvela (1995). The array was collecting data for two years with a trigger rate of about 5 mHz (400 per day).

2.1 The experimental arrangement

Four Fast Timing plastic scintillators (FT's, solid squares in Fig. 1) recorded the hit times of the shower front on the FT's relative to the central FT1. The four-fold coincidence of the FT-pulses was also used to trigger the data collection. Eight liquid scintillators, the Density Detectors (DD's, open squares) were arranged side by side in four pairs. They were used to record the densities of the electro-magnetic component of the shower. In the centre of the array (open square with cross) there were, one above the other, a pair of DD's, the central FT1, and the hadron spectrometer (HS) which

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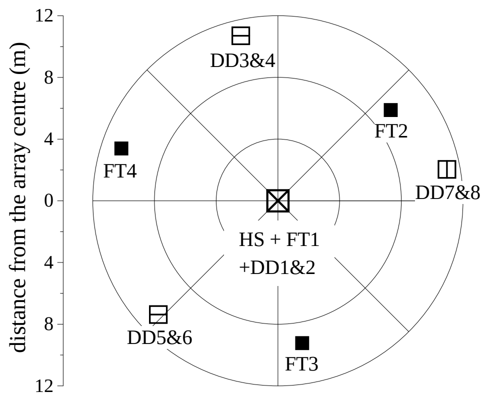

Fig. 1. The air shower array in Turku. The labels are explained in the text.

consisted of two overlapping neutron monitors. The multiplicities of the evaporation neutrons in the HS were recorded in connection with air showers. They were used to evaluate the upper limit of hadron energy flow in the array centre in connection with the air showers (Arvela, 1997).

2.2 Shower analysis

The analysis program first determines the shower arrival direction, i.e. the zenith angle θ and the azimuth angle ψ, using the FT-data (Elo and Arvela, 1997a). Then the numbers of particles hitting each DD and the corresponding particle densities are evaluated. Finally this data is fitted with the Nishimura-Kamata-Greisen lateral distribution function for electro-magnetic particles in the shower (Greisen, 1960):

$$\rho(r,s,N) = \frac{N}{2\pi r_0^2}\, g(s) \left(\frac{r}{r_0}\right)^{s-2} \left(1+\frac{r}{r_0}\right)^{s-4.5}, \qquad (1)$$

$$g(s) = \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)}.$$

Here $\rho(r,s,N)$ is the particle density at distance r from the shower core, s is the age parameter, N is the shower size, r_0 is the scale length, the so-called Molière radius, and Γ is the gamma function. Values s = 1.4 and r_0 = 79 m are adopted in the present analysis. The fitting procedure is described by Arvela et al. (1991), and in detail by Arvela (1997).

The fit gives as results the shower core's landing position (X, Y) in the array's co-ordinate system and its distance R from the array origin, the shower size N, and the upper limit of the hadron energy flow E in the centre of the array.

2.3 Shower selection

Our analysis program checks the validity of both intermediate and final results obtained in the successive sub-routines. If at any point the result does not fulfil the pre-set criteria the event is rejected and the analysis aborts. Each failure also generates its own error code, which together with event identification data is written in a 'bad data' file. In the following the shower selection criteria concerning only the timing and direction determination are described. A full description is given in Arvela (1997).

The FT's were monitored on a rather loose coincidence condition in order not to miss any showers. This naturally led to false triggers, too. The DD-data was therefore utilised as an additional off-line shower trigger: a pulse height corresponding to at least one-half muon in at least one DD in every DD-pair was required. Failing this condition resulted in rejection of the event.

The arrival direction of the shower is determined using the timing data from the three peripheral FT's and the plane approximation of the shower front. If the arrival direction obtained is impossible (e.g. from below the horizon), or the distances of the detectors and the detected time differences do not match, the event is discarded. Otherwise the analysis program then calculates for this direction an expected hit time of the shower front on the central FT1. This is then compared with the measured hit time. The event is discarded if the difference is larger than a pre-set limit based on estimated timing precision of the experiment (10 ns in the present analysis).

3 Results

3.1 Previous results

We have in our previous works (Arvela, 1997; Elo and Arvela, 1999a) determined the arrival direction distributions for our shower data. Instead of being even as expected the obtained azimuth direction distribution was sinusoidally modulated so that in the direction of FT3 there was a deficit of showers. Correspondingly there was an excess of them in the opposite direction.

We have shown (Elo and Arvela, 1999b) that such distortions are due to timing inaccuracies in the measurement system, i.e. inappropriate differences in the delay lines of the FT-detectors. Further on, we have described (Elo and Arvela, 1999c) a method to determine proper timing corrections. These are now applied in our analysis program.

3.2 Shower database

We have analysed the shower data from an 18-month period using our strictest set of selection criteria. This led to a very high rejection rate of events: about 95 % of events were discarded. About 90 % of the rejections were caused by a single error and in the rest there were multiple errors.

The unequivocal majority of reasons for rejection had to do with too low particle densities in the DD's, which had to be high enough to ensure sufficient statistics for a reliable shower analysis (Arvela et al., 1993).

The most usual reason for rejection not involving too low particle densities was the failure of direction determination or that the FT1-timing data was found incompatible with the

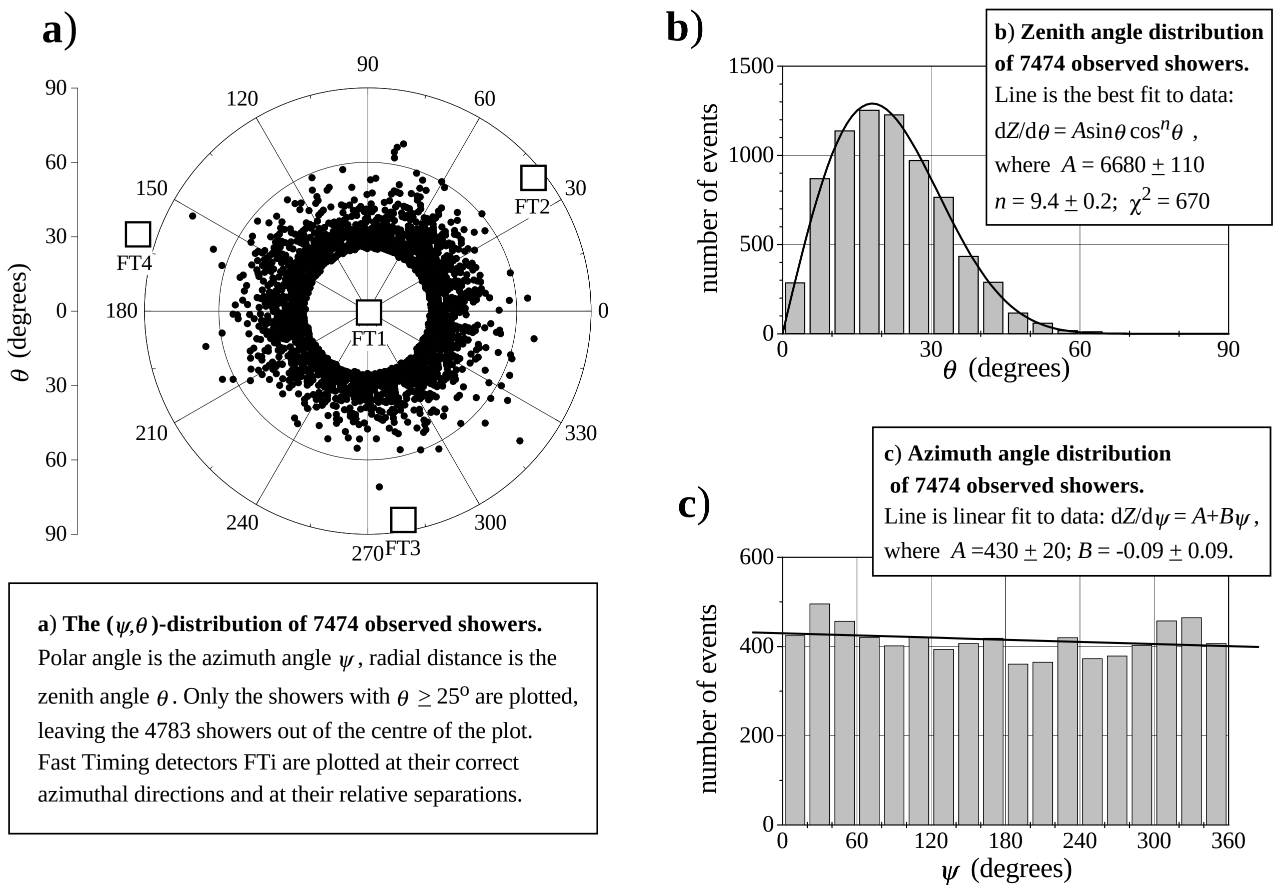

Fig. 2. a) the (ψ,θ) -distribution, b) the differential zenith angle distribution, c) the differential azimuth angle distribution of observed showers.

other FT-detectors. This situation was encountered in few percent of the cases as the single reason for rejection. It also occurred in multiple error situations together with the above mentioned 'too low particle density' errors.

We ended up with 7474 good shower events and the following results are deduced from this data.

3.3 Arrival direction distributions

The arrival direction distributions are shown in Fig. 2. In panel a) the (ψ,θ)-distribution of detected showers is shown. Each shower is marked with a dot, whose polar angle corresponds to the azimuth direction ψ while its radial distance gives the zenith angle θ. The FT's are also shown in the graph on their proper azimuth directions and relative distances with the central FT1 in the origin. Showers with $\theta < 25°$ are not plotted in order to 'save ink'. There are in the centre of the plot 4783 of such showers made invisible.

The flux of air showers grows with increasing zenith angle θ due to the increase of solid angle proportionally to sinθ. The influence of atmospheric absorption, however, outweighs this increase at larger zenith angles as this effect is growing even faster. The resulting differential zenith angle distribution can be described with the relation

$$\frac{\mathrm{d}Z}{\mathrm{d}\theta} \propto \sin\theta\cos^n\theta. \tag{2}$$

In panel b) of Fig. 2 the differential zenith angle distribution of observed showers is shown, together with a fit to the data according to Eq. (2).

The best fit to the observed data is obtained with the exponent n = 9.4 ± 0.2. The fitted curve reaches the maximun with zenith angle $\theta = 18°$. The average zenith angle of the observed showers is $\langle\theta\rangle = 22°$. Only 3 % of the showers had zenith angles larger than 45°. About 90 % of the showers in this analysis were in the shower size range $7{\times}10^4 \le N \le 3{\times}10^5$.

In Fig. 2 c) the observed differential azimuth angle distribution is shown together with a linear fit, which now with appropriate timing corrections is satisfyingly even: the slope is zero within the error limit.

3.4 Pointing accuracy

An often-used but crude estimate for the pointing accuracy of an air shower array is calculated from the expression

$$\Delta\theta \approx \frac{c\Delta t}{d}\ , \tag{3}$$

where Δt is the accuracy of the shower front arrival time measurement, d is the so-called base line of the array, i.e. the separation of detectors, and c is the velocity of light. Quite often Δt is simply taken to be the accuracy of the Time-to-Digital-Converter (TDC) being used, neglecting all other factors affecting the timing accuracy.

A more realistic value is obtained when Δt is estimated by calculating the shower front hit time for a detector not used in the direction determination, and comparing it to the hit time measured with that detector. Application of this method to the FT1-data produces time difference distribution with standard deviation $\sigma < 4$ ns. Together with the base line d = 17 m this gives pointing accuracy of about 4° for our array.

4 Discussion

The exponent n = 9.4 $\pm$ 0.2 obtained for the zenith angle distribution in Eq. 2 is in concord with the findings of other workers (Ashton et al., 1979; Sun and Winn, 1984; Plunkett et al., 1991). It is also fairly close to the approximate value 8.3 given by Cocconi (1961).

The estimate for the pointing accuracy for the air shower array in Turku, 4°, is quite satisfactory for such a small array. Our direction determination is based on minimum number of timing detectors, leading to the simplest calculation but also to the most uncertain result (Smith, 1978). When more detectors are used the direction determination involves more complex calculations but simultaneously the accuracy of the direction determination improves.

Our previous calculations (Elo and Arvela, 1997b) indicate that the absolute upper limits of the errors in the direction angles $\Delta\theta$ and $\Delta\psi$ are, however, rather high. Even with good timing accuracy Δt = 1 ns they may easily multiply exceed the above estimate. Therefore we take up a rather cautious attitude towards values deduced as in Sect. 3.4.

Our measurement system was slightly modified a few times during the experiment as e.g. new equipment or measurements were introduced, requiring also small alterations in the timing measurement arrangements. Obviously they were not always carried out carefully enough, resulting in changes and slight mismatches in the delays of the FT-lines. – The FT's did not lie on the same horizontal level due to physical constraints of the laboratory building on which they were situated. This fact did not make the design of the timing easier.

The direction distributions in Fig. 2 no more display features indicative of inaccurate timing: the arrival directions are centred round the zenith and are evenly distributed in the azimuth. Thus we may conclude that we have found appropriate timing corrections for our analysis.

The shape of the azimuth direction distribution is very easy to check and it reveals explicitly whether there is something wrong in the timing of the measurement system. Therefore it is highly recommendable that it be carried out as a routine test of an air shower array's performance.

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