THICKNESS OF THE PARTICLE SWARM IN COSMIC RAY AIR SHOWERS

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ABSTRACT

The average dispersion in arrival time of air shower particles detected with a scintillator at an impact parameter r is described with accuracy 5-10% by the empirical formula $<\sigma> = \sigma_{to}(1 + r/r_t)^b$, where $\sigma_{to} = 2.6$ ns, $r_t = 30$ m and $b = (1.94\pm.08) - (0.39\pm.06) \sec\theta$, for $r < 2$ km, $10^8 < E < 10^{11}$ GeV, and $\theta < 60°$. (E is the primary energy and θ is the zenith angle.) The amount of fluctuation in σ_t due to fluctuations in the level of origin and shower development is less than 20%. These results provide a basis for estimating the impact parameters of very large showers with data from very small detector arrays (mini-arrays). The energy of such showers can then be estimated from the local particle density. The formula also provides a basis for estimating the angular resolution of air shower array-telescopes (conference paper OG9.5-6).

1. Introduction. The particles making up an air shower (AS) travel in a swarm which is remarkably compact near the shower axis. Within 10 m of the axis the thickness is only a meter or two (Bassi *et al.* 1953). But when the thickness was measured at much greater distances it was found unexpectedly to be much greater, tens to hundreds of meters (Linsley *et al.* 1961, hereafter LSR; Linsley and Scarsi 1962, hereafter LS). This result, like the earlier one, was derived from arrival time measurements with scintillators. In reporting it primary emphasis was given to $t_{\frac{1}{2}}$, the median delay with respect to the shower plane. This is a plane perpendicular to the axis through the central portion of the particle swarm, determined from timing data at relatively small distances. It was shown that for a given impact parameter r, the median delay decreases with increasing zenith angle θ, and it was pointed out that by a simple kinematic argument the median time delay of the essentially unscattered muon component (observed in the same experiment using a shielded scintillator) provides an estimate of the median production height of the muons (LS).

This behavior at large distances was soon confirmed by J.G. Wilson and his collaborators using an array of deep water Cerenkov detectors at Haverah Park. Painstaking studies showed that $t_{\frac{1}{2}}$ measured with these detectors depends not only on θ but also on primary energy (Baxter *et al.* 1965, Walker and Watson 1981). They showed, moreover, that for given θ and E, $t_{\frac{1}{2}}$ fluctuates, presumably as a result of variability in starting points and subsequent development of AS, possibly also because of differences in mass of the primary particles (Walker and Watson 1982).

The early results near the axis have been confirmed (Woidneck and Böhm 1975, Sakayama and Suzuki 1981), but until recently no further results had been reported on arrival times measured with scintillators at large distances, nor had data been published on measures of thickness other than $t_{\frac{1}{2}}$ (and $<t>$, the average particle delay). Presently there is renewed interest in AS thickness at large core distances for 3 reasons:

1) a disagreement between the S(600) spectrum (equivalent to the primary cosmic ray energy spectrum) reported by a group in Yakutsk (Diminstein *et al.* 1982) and similar results obtained in the Volcano Ranch and Haverah Park experiments (Bower *et al.* 1983). It has been suggested that this may result from some peculiarity of the Yakutsk electronic system related to signal durations (Bower *et al.* 1982),

2) the presence of so-called SLP's (sub-luminal pulses) observed with scintillators, apparently caused by the low energy nucleon component of AS (Linsley 1984),

3) a suggestion for using pulse widths to measure AS impact parameters, increasing by an order of magnitude the area that can be made sensitive to 10^{20} eV cosmic rays for a given cost (Linsley 1983, Brooke *et al.* 1983, Hazen and Hazen 1983, Clay and Dawson 1984).

In response to this interest, records from the Volcano Ranch experiment (oscilloscope photographs) have been re-examined. Given here are results from this re-examination, together with new results derived from previously published Volcano Ranch data (LSR, LS).

<u>2. Arrival Time Dispersion.</u> In some applications, notably (3) above, the shower plane may not be well determined by the data, so an appropriate measure of shower thickness is the separate event arrival time dispersion defined by $\sigma_t = [\int(t-\langle t\rangle)^2 p(t)dt]^{\frac{1}{2}}$, rather than $t_{\frac{1}{2}}$, where p(t) is the probability of a particle arriving in time interval dt. Volcano Ranch records provide 3 avenues by which estimates of σ_t can be obtained:

1) a previously published set of signals from a certain unusually large AS, notable because they afford good statistical accuracy at quite large impact parameters,

2) previously published arrival time histograms for single particles in smaller AS, affording good statistical accuracy at smaller impact parameters,

3) original photographic records of 16 especially large AS from 1962-63.

It is shown that an empirical formula which fits the data at smaller impact parameters (average small AS, data set 2 above) is consistent with the data at larger impact parameters (set 1). It is then shown by means of the previously unpublished data (set 3) that the single large AS is in fact typical, and that pulse width fluctuations are tolerably small. Data set 3, containing events with θ ranging from 7° to 55°, also yields the zenith angle dependence of $\langle\sigma_t\rangle$.

Data set 1 consists of 8 graphically deconvoluted signals from scintillators at impact parameters > 1.3 km. The estimates of core location, size and energy for this event (LSR) have since been revised on the basis of a detailed study of shower structure (Linsley 1977). The final values used here are given in the *Catalogue of Highest Energy Cosmic Rays*, together with values of many subsidiary quantities for the same event, No. 2533 (size $1.1 \cdot 10^{10}$ particles, $E = 5.6 \cdot 10^{19}$ eV, $\theta = 42°$; Linsley 1980). For the present purpose the signals were sorted into 2 groups according to r, and those in each group were combined. For each group the dispersion is given in Table 1 with standard estimates of the statistical error.

Table 1. Width of signals, AS No. 2533

av. r (km)	No. of particles	mean delay (ns)	dispersion (ns)
1.45	91	840 ± 60	610 ± 45
1.80	33	1260 ± 200	1140 ± 140

It was stated in LSR that this event is typical, meaning that 1) to first order the arrival time distribution is independent of shower size or zenith angle, depending only on r, and 2) for given N, θ, r the fluctuations in this distribution due to variability in starting points, development, etc. are relatively small. If this is correct then the dispersion values given in Table 1 will be consistent with those obtained by the method of LS, in which distributions for various r intervals were built up from single particle delays for many AS with widely ranging values of N (shower size) and θ. Results on dispersion were not given in that article, so they have now been calculated from the single particle delay histograms that were given. The new results are listed in Table 2. Inspection shows that they are reasonably consistent with those for the one large event (Table 1), and that all of the data, including data at small core distances referred to in the Introduction, can be represented by the empirical formula

$$\langle\sigma_t\rangle = \sigma_{to}(1 + r/r_t)^b \qquad (1)$$

with σ_{ot} = 2.6 ns, r_t = 30 m, and b ∿ 1.5. When these fixed values are taken for σ_{ot} and r_t, the value of b controls the fit at large distances. A best value for b will be determined next from data set 3.

The original records for all years of Volcano Ranch operation except the last one (1962-1963) have been lost, so it is not possible to re-examine the record of event No. 2533. Records still exist, however, for more than 500 large AS, including 16 which satisfied the condition (E > 10^{19} eV) for being listed in the *Catalogue of Highest Energy Cosmic Rays*. The proposed method of determining r (and hence E) from σ_t and S (integrated particle density) at a single location was tested using these 16 events (Linsley 1983). An intermediate result of the test is another set of σ_t values given in Table 3. Because they belong to different events these values will reveal whether fluctuations of σ_t are likely to be troublesome. By agreeing fairly well on average with Table 1 they show that No. 2533 is indeed typical of AS with E > 10^{19} eV. By agreeing on average with Table 2 they show that $\langle\sigma_t\rangle$ hardly changes between 10^{17} and 10^{19} eV.

The Volcano Ranch array consisted of 19 detectors. For events such as these most of them were struck by one or more particles. The first step was to select in an unbiased manner one pulse per event. It should not be too small because of statistical errors nor too large because of electronic distortion. The one chosen in each case is the one with greatest S such that S < 7 m^{-2}. The number of particles contributing to the various AS pulses (n = AScosθ, where A is the de-

Table 2. Width of single particle arrival time distribution

r (km)	No. of particles	mean delay (ns)	dispersion (ns)
0.46	62	238 ± 20	152 ± 10
0.55	202	271 ± 17	242 ± 12
0.65	289	307 ± 16	280 ± 12
0.75	193	330 ± 24	329 ± 17
0.85	161	534 ± 35	448 ± 25
0.95	167	475 ± 39	508 ± 28
1.10	169	649 ± 50	671 ± 36
1.35	88	683 ± 73	660 ± 50

Table 3. Width of separate event arrival time distributions

serial number	θ (deg)	r (km)	No. of particles	dispersion (ns)
4827	28	1.3	17	490 ± 80
4835	31	1.7	10	1040 ± 230
4860	12	1.3	19	710 ± 120
4882	40	2.0	9	880 ± 200
4906	25	1.1	19	1090 ± 180
4925	7	1.3	12	690 ± 140
4929	55	1.4	11	200 ± 40
4946	37	1.2	13	760 ± 150
4985	39	1.3	9	690 ± 170
5005	23	1.3	10	860 ± 190
5051	40	1.2	9	350 ± 80
5059	31	1.6	6	1550 ± 450
5072	32	0.9	18	540 ± 90
5171	54	1.2	10	380 ± 90
5216	16	1.3	22	920 ± 140
5280	52	1.5	8	750 ± 190

tector area, 3.26 m^2) ranges from 6 to 22, averaging 12. The values of r range from 0.9 to 2.0 km, averaging 1.4 km.

The AS pulses and a bandwidth-limited (BWL) test pulse were digitized and the dispersions were calculated. The dispersion of the input signal was taken as $(\sigma^2_{obs} - \sigma^2_{BWL})^{\frac{1}{2}}$. Sub-luminal pulses, present in 2 cases, were disregarded in calculating σ_{obs}. Thanks to an astute anonymous reviewer it was noted that the data of Table 3 contain useful information about the zenith angle dependence of $\langle\sigma_t\rangle$. A convenient way to express this is through the parameter b in (1), by letting $b = b_1 + b_2 \sec\theta$. By use of least squares one obtains $b = (1.94\pm.08) - (0.39\pm.06) \sec\theta$. Using this expression in (1), there is excellent agreement between Tables 1, 2 and 3. The individual values of $\sigma_t/\langle\sigma_t\rangle_{calc}$ have about 3 times the variance expected from the simple statistical errors. The excess variance is due in part to systematic differences in primary energy and possibly primary mass, in part to random instrumental errors, and in part to AS fluctuations. By neglecting the first two types of contribution one obtains an upper limit of 20% for the amount of fluctuation in σ_t due to fluctuations in level of origin and shower development.

3. Conclusions.

Eq. 1 with σ_{to} = 2.6 ns, r_t = 30 m, and $b = (1.94\pm.08) - (0.39\pm.06) \sec\theta$ represents the average dispersion in arrival time of AS particles as measured with scintillators when SLP's are excluded. The dispersion is not strongly energy dependent over the range $10^8 < E < 10^{11}$ GeV. The fluctuation in σ_t due to fluctuations in level of origin and shower development is less than 20%.

References.

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