SUB-LUMINAL PULSES FROM COSMIC RAY AIR SHOWERS

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ABSTRACT

Some of the signals produced by air showers in scintillators possess a distinctive feature, a 'sub-luminal pulse' (SLP) following the normal one with a time delay of approximately 1.5 r/c. The average amplitude of the SLP corresponds to an energy deposit of about 50 MeV, three times as much as is deposited in a typical scintillator by vertical minimum ionizing muons. The SLP account for approximately 5% of the energy deposited in the atmosphere by air showers with energy > 10^{10} GeV at impact parameters > 1 km. Assuming with Greisen that these pulses are due to neutrons travelling with a speed slightly less than c, they provide a unique means of estimating E_h, the energy deposited by slow hadrons, in showers of this very high energy. On the other hand, if not allowed for properly, these pulses are liable to cause errors in estimating the impact parameters of large showers from pulse width observations.

1. Introduction. There are two reasons for regarding the phenomenon reported here as more than a mere curiosity: 1) it may prove to be useful as an additional indicator of primary mass, and 2) if it is not taken into account properly it can cause errors in estimating shower size from measurements of particle density and arrival time spread by means of a mini array (Linsley 1983).

When air showers (AS) were first observed at very large values of the impact parameter it was found that signals produced in thin scintillators were unexpectedly broad (Linsley *et al.* 1961, Linsley and Scarsi 1962). Recently some of the records of the experiment were re-examined in connection with a controversy about very large AS with E > 10^{10} GeV (Bower *et al.* 1982, 1983). Such records (oscilloscope photographs) still exist for more than 500 events registered during 1962-63, including 16 which were qualified, by satisfying the above energy condition, for inclusion in the *Catalogue of Highest Energy Cosmic Rays* (Linsley 1980). The experimental method as it relates to the present discussion is described by Linsley and Scarsi (1962); for a complete bibliography see (Linsley 1980).

2. Observations. It was noticed that the scintillator signals from these AS frequently possess a sort of after-pulse, called for reasons explained below an SLP (sub-luminal pulse). To account for the name, signals with delays < r/c can be produced by 'luminal' particles travelling at essentially the speed of light. Almost all particles in AS are of this type. Signals with greater delays require that the observed energy be transported from the shower core at 'sub-luminal' velocities appreciably < c. For r > 1 km such signals are easily recognized in the Volcano Ranch data

(double pulse resolving time ∿ 3 μs). Sixteen of them were discovered while re-examining the events listed in the *Catalogue*. Tracings are shown in Fig. 1, together with tracings of a typical bandwidth-limited (BWL) test pulse and a typical train of 1 MHz timing pulses.

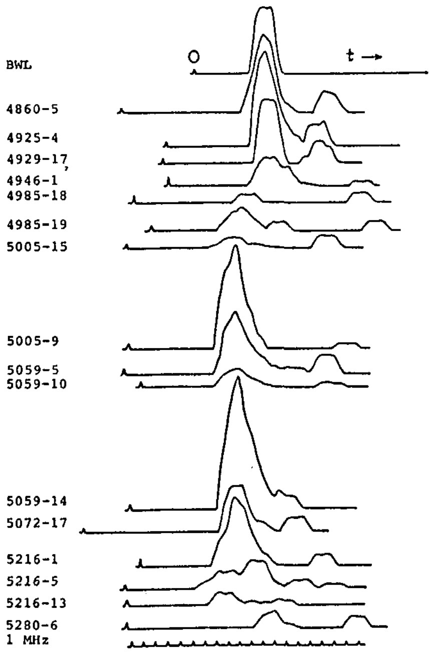

Fig. 1. Scintillator signals showing SLP, identified by event No. and channel No., with a typical bandwidth-limited test pulse (BWL) and a typical train of 1 MHz timing pulses.

In order to rule out instrumental effects such as photomultiplier after-pulsing as the source of delayed pulses, the following tests were made:

1) All 1962-63 AS signals in the same size range as signals preceding the Fig. 1 SLP were scanned for the presence of delayed pulses. (The pulses preceding the SLP have integrated charge values 4 to 40 times the average for vertical minimum ionizing muons.) In 132 cases out of 1648 the prompt pulse was followed after 3 to 10 μs by a well defined delayed pulse (DP). It was determined that the fraction of DP was the same within statistical errors for all 19 channels corresponding to the 19 scintillators making up the Volcano Ranch array.

2) The 1648 DP candidates were then sorted according to shower size, using bins a factor of 2 in width. It was found that the showers in the two lowest-size bins (41 candidate pulses) had no DP, and that showers in the next higher bin (169 candidates) had only 3 DP. The fraction of DP in larger showers increased steadily as shown in Fig. 2, reaching a value ∿ 0.2 for the highest 3 bins.

While it is not quite true that pulses of a given size from large showers are *identical to* pulses of the same size from smaller showers, the differences there are, in average pulse duration, fail to account for the strong shower size dependence seen in Fig. 2. Ignoring therefore the differences there are, in pulse duration, I take it that the fraction of DP in small-shower pulses gives an upper limit for the percentage of DP that might be spurious. I conclude that no more than 10% of the DP in large showers (size $N > 10^9$) are in fact instrumental, or accidental.

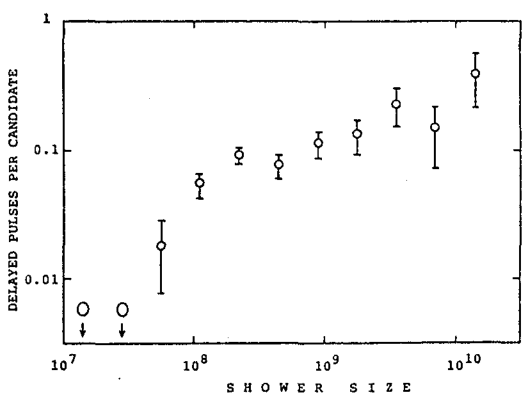

Fig. 2. Fraction of signals with delayed pulses vs shower size, for densities 4-40 particles per 3.26 m^2 scintillator area.

In case of very large showers (highest 3 bins) about half of the DP are sub-luminal. The trend seen in Fig. 2 can be explained as follows:

as one goes from very large showers to smaller ones (right to left in the figure) the impact parameter corresponding to the accepted range of pulse amplitudes decreases, and so does the critical delay separating the luminal and sub-luminal regimes. By the time one reaches shower size $3\cdot10^8$, nearly all DP (which are required to have delays > 3 μs so as to be clearly resolved) are sub-luminal. As one goes to still smaller sizes the SLP begin to merge with the prompt pulses, until finally (for $N < 3\cdot10^7$) all of them have merged, and no more DP are found using the definition adopted here.

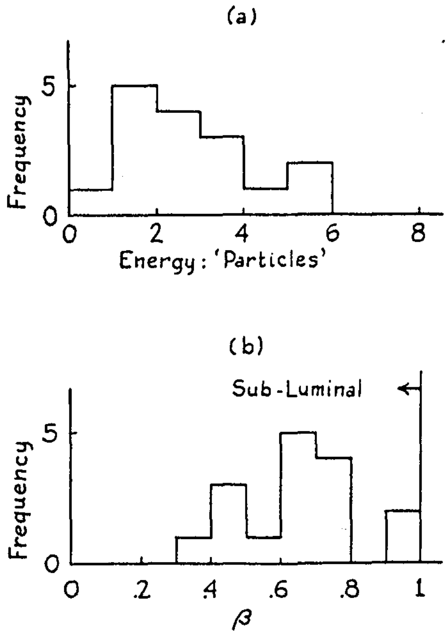

Fig. 3. Distribution of deposited energy (a) and transport velocity (b) for 16 SLP.

3. Results and discussion. The amplitudes of the Fig. 1 SLP (apparent particle densities) show that the average amount of energy deposited in the scintillators is about 50 MeV, 3 times as much as is deposited by a vertical minimum ionizing muon (see Fig. 3a). If the scintillations are produced by heavily ionizing secondaries, as the low transport velocity suggests may be the case, then the actual deposited energy will be somewhat higher because the response of the plastic scintillator to heavily ionizing particles is nonlinear (Korff 1962).

The time at which the earlier pulse begins (see Fig. 1) corresponds to passage of the shower plane, a plane perpendicular to the axis through the central portion of the particle swarm, determined by means of detectors at relatively small core distances. In most cases the SLP (latest pulse) has no structure; its shape indicates that the energy is deposited in a time interval too small to be resolved. Exceptions are 5216-5 and possibly 4860-5. In case of 4929-17 the latest pulse is a superposition of 2 BWL signals. Only the later, larger one satisfies the condition: delay (with respect to the shower plane) > r/c. With two exceptions, the one just noted and 5059-14, the SLP seem to be completely resolved from the normal particles by that condition alone. Additional evidence that SLP are a distinct phenomenon is given by Fig. 3b. The most frequent examples are not the ones that just marginally satisfy the selection condition, they are those with time delay ~ 1.5 r/c ($\beta \sim 0.7$).

Fig. 4 shows the ratio of SLP to normal particles in various r intervals, for all signals with particle density < 10 m^{-2} (hence sufficiently undistorted by the electronic system for DP to be recognizable) and r > 1 km. The average ratio is (1.6 ± 0.4)%, and there is no evidence of any r dependence. This fact, and the fact that SLP occur in AS with zenith angles in a broad range (7° to 55° for this sample) suggests that the component which causes them is in equilibrium with the normal particles. Under this assumption the energy deposited in the form of SLP amounts to about 5% of the primary energy. (The scintillation plastic

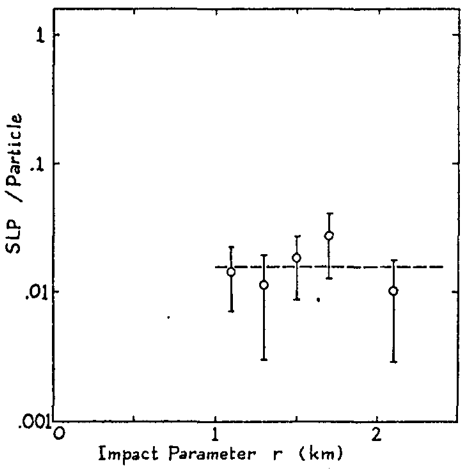

Fig. 4. Abundance of SLP vs impact parameter.

has a composition similar to air.) The explanation of Fig. 2 offered above is based on the same assumption.

4. Conclusions. Commenting on the result of Linsley and Scarsi (1962) in the light of his own observations using similar equipment, Greisen opined that "some of the delayed pulses with large delays...are due to neutrons travelling at a speed slightly lower than light" (Greisen 1962). Assuming that SLP and the pulses referred to by Greisen are the same, and accepting his suggestion as to their cause, one notes that for AS with much lower total energies $\sim 10^6$ GeV the percentage dissipated by low energy hadrons is estimated to be 4 or 5% (Greisen 1956, Zatsepin *et al.* 1963), which agrees at face value with the estimate from Fig. 4. But the equilibrium hypothesis needs further testing. In any case, one must still explain the amplitude and delay distributions (Fig. 3). Aside from the present work the only experimental evidence on low energy nucleons in showers with energy > 10^6 GeV is from data taken with a neutron monitor at the Yakutsk array (Kozlov *et al.* 1981).

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