ble by now. By the time the universe had expanded to nuclear density, $\rho \simeq 2\times 10^{14}$ g/cm^3, the viscosity could be ignored and the model could be fitted onto one of the models which have been worked out for the "early" universe.

Under such extreme conditions one would expect graviton production in graviton-graviton scattering. This would lead to an increase in entropy which could be described crudely by a second viscosity coefficient. Of course in such a state, when the observable universe would be squeezed into a volume approaching that of a classical electron, any simple model can be considered only the crudest approximation. The gravitons of which I have spoken cannot at all be separated from the general curvature of space-time and a detailed description in terms of the single concept of second viscosity in not to be thought of. But it does seem possible that the model presented here might serve as a starting point for a more complete description.

*This paper is a slightly modified version of one which was awarded an honorable mention in the 1973 Gravity Research Foundation Essay Contest.

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Search for Correlations in the Arrival Times of Extensive Air Showers and Weber Gravitational Waves*

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We have searched for correlations in the arrival times of extensive air showers and Weber gravitational waves. Extensive air showers with energies greater than 5×10^{14} eV were detected at the Jadwin Physics Building, Princeton, New Jersey, from March to November 1971. The apparatus was not sensitive to cosmic rays coming directly from the galactic center. The shower-arrival times were compared to the arrival times of Weber's gravitational waves occurring over the same period. Undelayed- and delayed-time coincidences were checked for in the analysis, as well as possible time-delay dispersion effects.

INTRODUCTION

Several mechanisms have been proposed for generation of the gravitational waves detected by Weber.[1] Weber[2] and others have proposed that collapse of a star would give rise to gravitational waves. Misner[3] and others have conjectured that the gravitational waves are generated by synchrotron radiation of massive orbiting bodies. The most recent conjecture[4] is that they are associated with the recently discovered periodic x-ray sources.

It is possible that extremely high-energy particle emission would occur simultaneously with gravitational wave emission for any of the above-mentioned sources. For example, there could be strong internal or local electromagnetic fields occurring with collapse of a star that would accelerate particles to extremely high energies, or possibly the rapidly changing gravitational field could produce particles according to the theory proposed by Parker.[5] Another possibility is prompted by the suggestion that the change in period of the recently discovered x-ray sources is associated with a large mass transfer from one body to another. This leads one to think that discharged mass might result as well.

In any case, it is not unreasonable to expect that some of the energy given off from a cataclysmic or noncataclysmic event would be simultaneously in the form of gravitational waves and particles ranging from the lowest-energy to the highest-energy cosmic rays seen. The simultaneous emission of gravitational waves and cosmic rays could, for example, give rise to the times of arrival of cosmic rays and gravitational waves coinciding—i.e., there would be time coincidences between gravitational waves and cosmic rays. If there are time dispersion effects due to slightly longer trajectories for the cosmic-ray particle paths, or delayed emission at the source, it should be possible to also check for these by statistical methods.

Other experiments have checked for underground neutrino,[6] microwave,[7] and x-ray[8] time coincidences, but none of these reported positive results. If there were high-energy cosmic rays generated with gravitational waves, we would expect to find that some of the arrival times of extensive air showers caused by neutrons, γ's, and neutrinos coincided with Weber pulse arrival times. This is because the paths of uncharged particles are not bent by the galactic magnetic field, and, therefore, uncharged particles do not suffer any time delays and dispersion.

We now calculate the time delays for charged and uncharged particles relative to a γ ray or

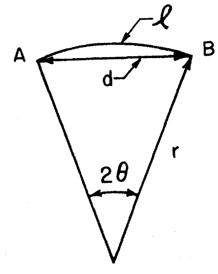

FIG. 1. Geometrical construction to determine delay time of charged particles.

gravitational wave. For an uncharged particle with mass traveling the same trajectory as a γ ray or gravitational wave, the time delay is due to the particle's velocity being less than c, the speed of light. Knowing its velocity, $v=\beta c$, we can calculate the transit time d/v, where d is the galactic distance. The time delay is then the difference in transit times $(d/v - d/c)$.

For a cosmic-ray neutron or other uncharged particle of total energy E and rest mass energy m_0c^2, we have

$$(1-\beta^2)^{-1/2}=(E/m_0c^2).$$

If we let $\beta = 1-\Delta$, where $\Delta \ll 1$, then

$$1-\beta^2 \simeq 2\Delta$$

and

$$(2\Delta)^{-1/2}=(E/m_0c^2)\ ,$$

$$(2\Delta)^{-1}=(E/m_0c^2)^2\ ,$$

or

$$\Delta = 0.5\,(E/m_0c^2)^{-2}.$$

Then

$$\beta=[1-0.5\,(E/m_0c^2)^{-2}]$$

and the transit time is $(d/c)[1+0.5\,(E/m_0c^2)^{-2}]$. The time delay is then $(d/c)\,[0.5\,(E/m_0c^2)^{-2}]$ between a particle with mass and a γ ray.

As an example, we calculate the time delay for a cosmic-ray neutron of energy 5×10^{14} eV, which is the minimum energy we are sensitive to in our experiment. We take $d=5\times10^{22}$ cm, the galactic radius. Substituting the neutron rest-mass energy ($\sim 10^9$ eV) and total energy into the expression for the time delay, we obtain the delay time,

$$T_D=[5\times10^{22}/(3\times10^{10})]\times(0.5\times0.04\times10^{-10})\ \text{sec}$$
$$=3.33\ \text{sec}\ ,$$

which is well within the 2-minute timing resolution of our experiment.

However, for charged particles, the time delay due to curvature in a magnetic field is much greater than the time delay due to the particles having nonzero rest mass. We demonstrate this now. Referring to Fig. 1 we consider that the cosmic-ray particle is emitted at point A and follows a curved trajectory, arc AB, to the shower detector at point B. The path length of the particle l for the idealized case of a magnetic field normal to the plane of the trajectory is $l=2r\theta$. If the particle traveled a straight line, the path length d would be $d=2r\sin\theta$.

For θ small, $d=2r(\theta-\theta^3/3!+\cdots)$. Then the difference in path length is $l-d\simeq 2r\theta^3/3!$. Now $\theta\sim d/2r$, and thus

$$(l-d)\simeq[2r/(8\times3!)](d/r)^3=(1/24)r(d/r)^3.$$

Now the radius of curvature is $r=pc/(300H)$, where p is the momentum in eV/c and H is the magnetic field in gauss. Then, for $pc=10^{20}$ eV (close to the upper limit of cosmic-ray energies) and $H=1\times10^{-6}$ gauss, the intergalactic field, we calculate that $r\cong3\times10^{23}$ cm. We then have $d/r\cong1.66\times10^{-1}$, taking an average distance for d equal to the galactic radius. Now $r\cong3\times10^5$ light years. Thus,

$$l-d\cong\tfrac{1}{24}r\times(1.66)^3\times10^{-3}$$
$$\cong 57 \text{ light years.}$$

Thus we see that the delay time of showers due to charged particles would be much too large to result in observable effects.

We now briefly discuss the neutral-particle types and the limitations imposed by their properties. Even though the proper lifetime of a neutron is only 1000 sec, for neutrons of energy greater than 10^{18} eV, the time dilation factor multiplying the proper lifetime is greater than 10^9. Hence there is only about a one-lifetime interval in the galactic reference frame for these neutrons to traverse a distance equal to a third of the galactic radius. If there are a large number originally produced, we could still be sensitive to the surviving fraction reaching earth. Neutrinos, being stable and having large cross sections at high energies, can reach the earth and produce extensive air showers without difficulty. High-energy γ's would have to pass through several interaction lengths to reach the earth because of background radiation. However, as with neutrons, if there are a sufficient number originally produced, an appreciable number could survive, even if the actual fraction reaching earth is small.

Very-high-energy cosmic-ray particles are known to follow a power-law spectrum $E^{-\gamma}$, where $\gamma\simeq3.4$ (See Refs. 9 and 10.) Using this, we may calculate what fraction, f, of the originally generated background contributing neutrons (where the neutron fraction of all cosmic rays is f_n) traveling a distance equal to $\frac{1}{3}$ of the galactic radius survive and are detected by our apparatus. The fraction is given by

$$f=f_n\,\frac{\int_{E=E_{\text{min, neutron}}}^{E=\infty}E^{-\gamma}e^{-t/\tau}A(E)\,dE}{\int_{E=E_{\text{min, total}}}^{E=\infty}E^{-\gamma}A(E)\,dE}\ .$$

Here,

$$\tau=[E/(m_0c^2)]\tau_0\ ,$$

the dilated neutron lifetime in the galaxy, where τ_0 is the lifetime of a neutron at rest (1000 sec), E is the neutron energy, and m_0c^2 is the neutron rest mass energy. Here t is the transit time required to go $\frac{1}{3}$ of a galactic distance. $E_{\text{min, neutron}}$ is the minimum neutron energy considered (10^{18} eV), and $E_{\text{min, total}}$ is the minimum energy considered of all particles (0.5×10^{15} eV). The factor $A(E)$ is proportional to the area of the shower due to an original cosmic ray of energy E over which the particle density Δ^2 is greater than $56/\text{m}^2$, the minimum density required to fire the apparatus. This factor is proportional to the probability of detecting a shower of energy E, and $A(E)$ is calculated using the density formula[9]

$$\Delta^2=N\frac{0.45}{RR_\lambda^{\,2}}(1.0+4.0R)\exp(-4.0R^{2/3})\ .$$

Here N is the total number of particles in a shower, taken as $6\times10^{-12}E^{1.1}$ (E in eV), R_λ is the interaction length (taken as 80 meters), and R is the radial distance (in units of R_λ) from the shower center. Then, taking as an estimate $f_n=\frac{1}{10}$—i.e., that $\frac{1}{10}$ of all the high-energy particles generated are neutrons (no data are available on this)—and using the previous equation, we obtain for the number, N_n, of neutron background events above 10^{18} eV out of the 1700 total events detected in this experiment the result

$$N_n\cong\tfrac{1}{10}\times1700\times4.6\times10^{-5}$$
$$\simeq7.82\times10^{-3}\ ,$$

where the last factor is the ratio of the numerically evaluated integrals. Thus, the expected number of background neutrons, as extrapolated from the known energy spectra, would be small.

We do not know how many of the extensive air showers of the energy we are sensitive to are due to neutrinos, γ's, and neutrons. We expect, from the delay-time calculations above, that only the fraction of showers caused by these particles would show correlations with the Weber pulses. For a given shower, we have no way of knowing the original particle type causing it, and thus we cannot obtain a "pure" sample of cosmic-ray showers expected to show correlations. However, we can consider the fraction of showers caused by these particles to constitute a sample which would give a signal—i.e., correlations—over a background of the showers due to charged particles. For example, if only ten of the showers out of the ~1700 recorded that overlapped with Weber's data were due to uncharged particles generated at the same time as the Weber pulse and traveling the same trajectories, we would obtain ten more zero delay time coincidences over the ten which we expect from randoms in this experiment, which would be statistically significant.

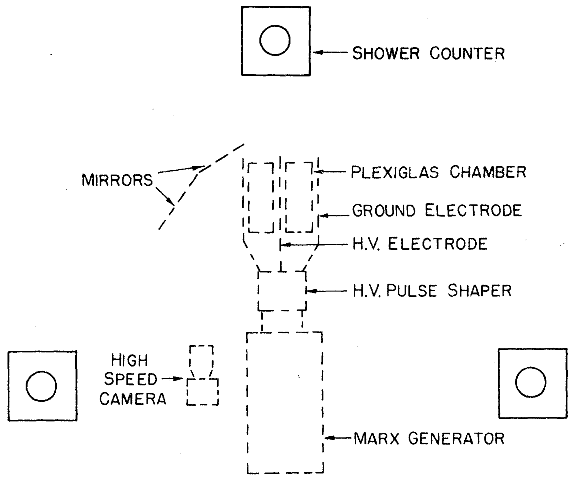

FIG. 2. Schematic layout of shower detection apparatus. The counters on the roof are drawn in solid lines. The streamer-chamber apparatus on the floor below is drawn in dashed lines.

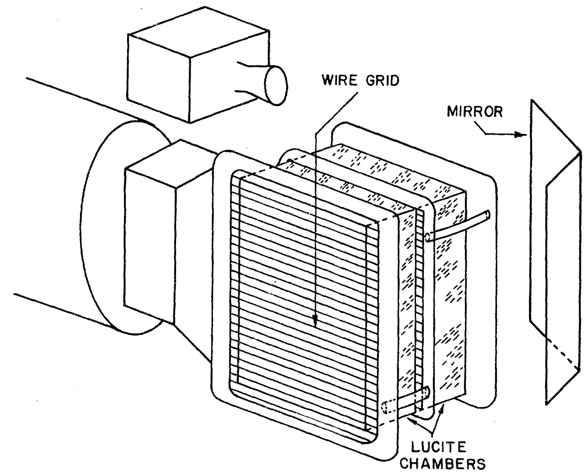

FIG. 3. Schematic of streamer-chamber layout.

APPARATUS

For this experiment, the arrival times of extensive air showers were recorded with a shower detector consisting of an array of four scintillation counters and a streamer chamber. The counters were located on the roof of the Jadwin Physics Building at Princeton, N. J. The streamer chamber was inside on the floor below. Coincidences between all counters fired the streamer chamber. The number of tracks observed in the streamer chamber gave a measure of the track density; the direction of the tracks provided the shower direction. Figure 2 gives a schematic representation of the apparatus. Three of the shower counters were placed at the corners of an isosceles triangle, 20 ft on a side. The fourth counter was at the center of the triangle directly over the streamer chamber. The minimum particle density required to fire discriminators on all of the counters was $56/\mathrm{m}^2$, as determined by the observed particle density cutoff in the streamer chamber.

The physical construction of the chamber was as shown in Fig. 3. The chamber consisted of two Plexiglas boxes placed between wire grids. The outer dimensions of the boxes were 16 in. × 4.25 in. × 25 in. and the inner dimensions were 15 in. × 3.75 in. × 24 in. The outer ground grids consisted of 30-mil-diameter Cu wires; the inner high-voltage grid was made of 16-mil-diameter hardened aluminum wire. The outer and inner wires of the grids were spaced 0.5 in. and 0.375 in. apart, respectively, and the spacing between the high-voltage grid and ground grids was 5 in.

The high-voltage pulse was generated by a ten-stage Marx generator as shown in Fig. 4, with each stage run at ±18 kV (for a total of 360 kV). C_m, the capacitance of each stage, was 16 000 $\mu\mu$F. The Marx generator proper was placed under pressure in a large tank. Both the generator and the tank were maintained at a dry nitrogen pressure of 30 lb/in.^{2}. The generator fed via 2.8-μH inductor into a pulse-shaping network, also shown in Fig. 4, which consisted of a final 250-$\mu\mu$F capacitor, a series spark gap which discharged the capacitor into the chamber, and a shorting spark gap which determined the time the high-voltage pulse was on the chamber. The chamber was terminated with two low-inductance $CuSO_4$-solution resistors of nominal resistance 500 Ω. The reflected high-voltage pulse broke down the shunt gap. The maximum high-voltage pulse height was 300 kV and the pulse width was 20 nsec as measured directly with a high-voltage probe feeding into a 517 scope. The high-voltage pulse occurred 0.75 μsec after passage of the shower.

The time to retrigger the chambers was limited only by the charging resistors of the Marx generator and high-voltage power supplies. This was about 5 sec. Thus it was possible to get rapid successive exposures as well as to trigger immediately after the shower occurrence. The memory time was measured to be 10 μsec for the impurity level of the chamber.

General Dynamics grade-A helium, 99.99% pure, was flowed through each chamber at a rate of 150 cc/min. No noticeable improvement in the track quality was observed with higher rates. The helium tank had to be replaced weekly at the flow rate used.

The streamers were photographed with a Soligar $f/1.5$, 135-mm-focal-length lens set at the maximum opening. The lens was mounted on a Flight

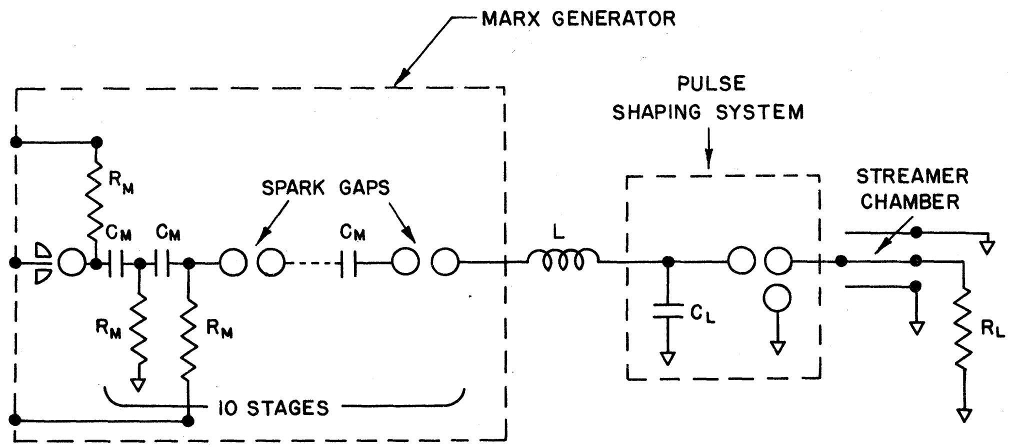

FIG. 4. High-voltage pulsing circuits.

Research 35-mm rapid-pulsing camera. As shown in Fig. 3, two mirrors were used, one providing a view along the electric field, and the other a 30° angled view for stereo reconstruction of the tracks. The lens was an optical length of 10 ft from the chamber center. A clock was photographed along with the streamer chamber in order to record the arrival times of the showers.

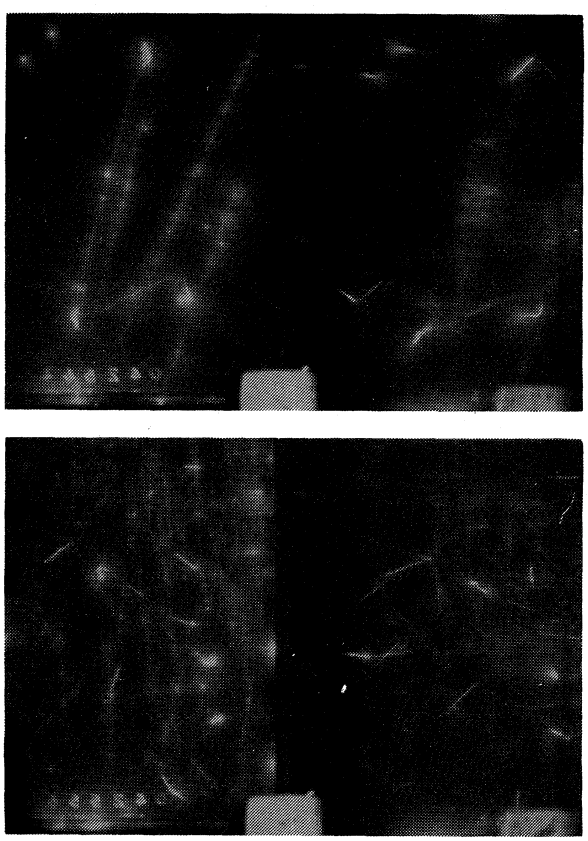

FIG. 5. (a) and (b) Examples of streamer chamber performance in extensive air showers. Electric field line and angled views are shown.

Kodak Tri-X was used to photograph the streamers, and was pushed to a speed of 1500 ASA by developing with Diafine developer. Tri-X had a resolution of 120 lines/mm. The high resolution was needed to make small streamers more easily seen. Diafine, while increasing the speed, also had the effect, however, of decreasing the resolution.

The chamber was operated almost continuously over the eight-month data-taking period. The only difficulties occurred when high-voltage power-supply drifts caused an over-voltage or under-voltage of the Marx generator spark gaps, thus causing spurious firing or no firing at all, respectively. The Marx generator operated reliably from 16 kV to 18 kV, the breakdown voltage. The discriminator settings on the shower array counters were adjusted so that the mean number of triggers obtained per day was 22. This corresponded, as determined from the minimum track densities in the streamer chamber, to a minimum shower energy of 0.5×10^{15} eV. This minimum energy was determined by comparing the minimum track densities against the Monte Carlo shower simulations of McCusker *et al.*[11] for 10^{15}-eV showers, with appropriate adjustments being made for the array size and shower energy.

About ten triggers per day gave ten tracks or more in the chamber, and about three per day gave more than 20 tracks (particle densities greater than $286/\mathrm{m}^2$). Figures 5(a) and 5(b) are typical shower pictures for Tri-X developed with Diafine.

DATA AND RESULTS: UNDELAYED COINCIDENCES

Extensive air showers were recorded from March 1971 to November 1971. Good data were recorded only for a total period of $4\frac{1}{2}$ months, since

TABLE I. Arrival times for extensive air showers and Weber gravity waves occurring in coincidence during the experiment. The time resolution ±2 min.

Date 1971	Arrival times (E.S.T.) Weber pulse	Air shower
April 18	1116	1118
April 26	1140	1139
April 26	1140	1142
April 26	1400	1359
May 8	1204	1202
No overlap data June, July, August		
Sept. 15	2226	2227
Sept. 22	0028	0029
Sept. 22	0046	0045
Sept. 29	1447	1447
Oct. 29	1646	1646

data collection time was lost due to malfunction and repair of the apparatus. The total time of overlap with Weber's data during this same period was 72 days. The mean extensive air shower rate m_1 for the experiment was 22.5/day. Weber's event rate, m_2, for the overlap period was 2.37/day. The mean rate m for a timing coincidence between extensive air showers and Weber pulses is $m=m_1m_2\,2\tau=0.14$/day, where τ is the time resolution (±2 minutes) of the apparatus. Thus, over a 72-day period, we would expect ten coincidences, on the average.

Table I shows the undelayed timing coincidences obtained between air shower and Weber pulse arrival times. The total number of ten is the number expected. However, it is seen that on April 26 there were coincidences with two Weber pulses occurring within 2 hours and 20 minutes of each other (less than 0.1 day). Also on September 22, there were two coincidences with Weber pulses occurring within 18 minutes of each other.

Let us define a coincidence pair as two coincidences occurring within a fraction of a day interval f of each other. In our case $f=0.1$. The probability that two coincidence pairs would occur during the time of the experiment can be calculated if the cosmic ray and gravity wave arrival times are assumed random and uncorrelated. Then the probability of occurrence of a single coincidence pair within any single fraction of a day interval f can be obtained by dividing the interval into n time bins where n is large.

It is then easily shown that the probability P of getting two coincidence pairs during an experiment of d days duration is $P\simeq\frac{1}{8}m^4f^2d^2$.

Substituting in the above expression the values of this experiment ($m=0.14$/day, $d=72$, $f=0.1$), the probability of occurrence of two coincidence pairs is 0.25%.

We have run computer simulations of the experiment by generating the time intervals between events randomly according to the distribution e^{-mt}. The value obtained for P from the computer runs is in agreement with the analytically calculated result.

Caution must be taken in interpreting the double coincidence pairs as positive results since the probability of finding anything unusual (whatever it may be) is certainly considerably higher than the 0.25% probability for just this type of "event" occurring. At best, the occurrence of this "event" can be taken only as evidence, and not as conclusive proof for extensive air showers being correlated with Weber pulses.

We have determined the position in the sky that the showers pointed to for the April 26 and September 22 coincidence pairs. The difference in the mean sidereal times is 2 hours and 41 minutes, which corresponds to an angular difference of 36°. The angular resolution of our apparatus is ±15°. Thus, considering that all showers were vertical, and taking the angular resolution into account, the showers are consistent with cosmic rays coming from the same direction. The vertical direction is towards Andromeda at the time of occurrence of the pairs.

The apparatus was essentially insensitive to cosmic rays from the galactic center, since the center is visible on the horizon at best only a few hours a day from Princeton, and the sensitivity of the equipment to cosmic rays at large zenith angles is low.

TIME-DELAY AND DISPERSION EFFECTS

If the cosmic rays are emitted either at a slightly later time (on the order of an hour) than the associated Weber gravitational waves and/or if they take a slightly longer time (again on the order of an hour) to travel the distance to the earth, we would expect the associated cosmic rays to arrive at a somewhat later time than their corresponding Weber pulses. The difference between the time of arrival of the cosmic ray and the time of arrival of its associated Weber pulse is called the time delay. If the time delays for all cosmic rays are the same or close to the same, we would expect to see effects in the coincidence rates—e.g., an increase—by delaying all the Weber arrival times a fixed amount equal to the delay time. The delay time would be found by successively increasing the Weber pulse delays till effects are found.

To search for fixed-time-delay coincidences, we have delayed all Weber event arrival times by a

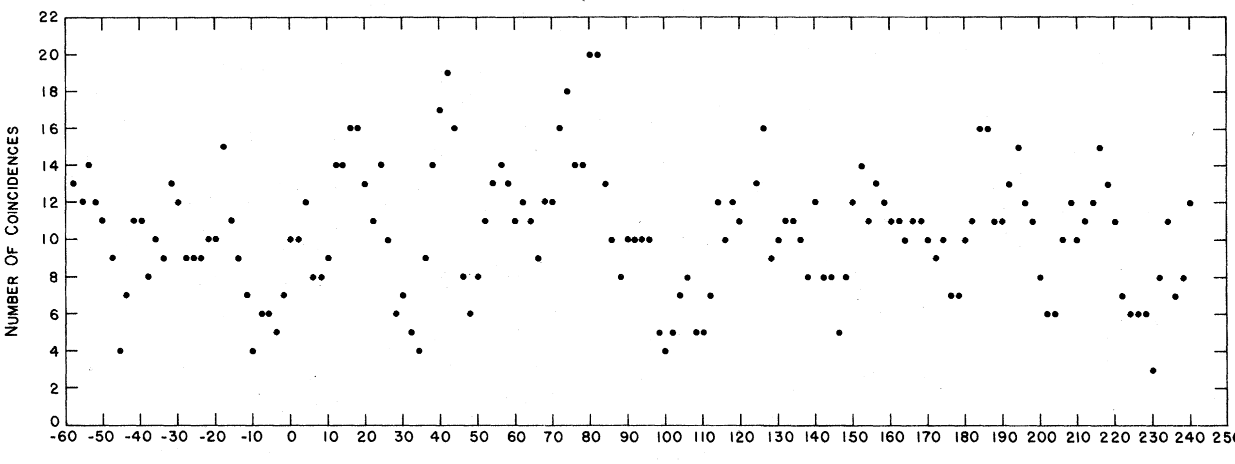

FIG. 6. Number of coincidences between extensive air showers and delayed Weber events as a function of delay time for Weber events. The time resolution is ± 2 min.

fixed amount of time and then checked for coincidences with the shower arrival times. The delay time varied from − 58 min to + 240 min in two-minute increments. It is unlikely that any effects would show up for greater delay times, since as the delay times and dispersion in time increase due, for example, to longer length trajectories, the rates will drop. Also, delayed emission at the source would not be expected to exceed a couple of hours. The number of coincidences as a function of delay time from − 58 min to 240 min are shown in Fig. 6. The coincidence numbers are distributed about a mean of 10.34 with a standard deviation of $\sqrt{11.38}$, which are close to the expected values of 10 and $\sqrt{10}$. The large number of coincidences (in parenthesis) for delay times of 42 minutes (19), 74 minutes (18), and 80–82 minutes (20) are all close to three standard deviations away from the mean value. Double pair coincidences for a fraction of a day interval $f = 0.1$ occur at delays (− 6, − 4), 0, 42, (54, 56) minutes. Parenthesis indicate at least one pair in common.

If the time delays are not constant, due, for example, to differences in path length of the cosmic rays, we would still expect that cosmic rays which are associated with the Weber waves would come somewhat sooner, on the average, after the Weber pulse than nonassociated cosmic rays.

The time interval between a cosmic ray preceding a Weber pulse and the Weber pulse and the time interval between the Weber pulse and a non-associated cosmic ray following it should, on the average, be the same. We have, therefore, compared the preceding time interval, T_P—which would represent the uncorrelated interval—to the following time interval T_f which would represent the correlated one. T_f should be less, on the average, than T_P if some of the cosmic rays following the Weber pulses are associated with them and are delayed a small amount of time relative to the Weber pulse.

To check for these short-time-delay dispersion effects, we ran a "difference t" test.[12] We compared the time interval T_p^i, the time interval between the arrival time of the air shower just prior to the ith Weber event and the arrival time of the Weber event, to T_f^i, the time interval between the arrival time of the same ith Weber event and the arrival time of the cosmic ray just following the ith Weber event. Defining $\Delta_i = T_p^i - T_f^i$, we calculated $\bar{\Delta} = (1/N) \sum_{i=1}^{N} \Delta_i$. Here the sum was over the $N = 172$ Weber events that occurred while we took extensive air shower data. According to the "t test," if $|t| \equiv |\bar{\Delta}|/(\sqrt{S^2}/\sqrt{N}) \geq 1.96$, the result is significant at the 5% level, where

$$S^2 = \sum_{i=1}^{N} (\Delta_i - \bar{\Delta})^2/(N-1).$$

We have obtained a value of $t = +0.72$ for this experiment.

We also ran a simpler "sign binary" test.[12] If the cosmic rays are uncorrelated with the Weber events, then, on the average, the number of positive Δ_i should equal the number of negative Δ_i. The number of positive (or negative) Δ_i should be distributed about a mean of $\frac{1}{2} N$, with a standard deviation of $[N(\frac{1}{2})^2]^{1/2}$. The data gave a result which, when corrected for continuity, was 1.4 standard deviations away from the mean towards positive Δ_i values, where 1.96 standard deviations would be significant at the 5% level.

Furthermore, we ran Wilcoxon's signed-rank test on the differences, and to compare the distribution of the positive differences to the distribution of the negative differences we did Wilcoxon's rank-sum test and Smirnov's D test.[13] None of these tests were significant at the 5% level.

CONCLUSIONS

In conclusion, the only evidence for correlations between the arrival times of extensive air showers and Weber gravitational waves was found in the occurrence of double pairs of coincidences. The probability of observing such pairs in this experiment for random uncorrelated arrival times was calculated to be less than 1%. If we say that one of these pairs may have been due to real correlated coincidences, we can set an upper limit of two true undelayed coincidences for this experiment.

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[12]See, e.g., G. W. Snedecor and W. G. Cochran, *Statistical Methods* (Iowa State Univ. Press, Ames, 1967). The "difference t" test is described on pp. 91–94. The "binary sign" test is described on pp. 125–127.

[13]J. V. Bradley, *Distribution-Free Statistical Tests* (Prentice-Hall, Englewood Cliffs, N. J., 1968).

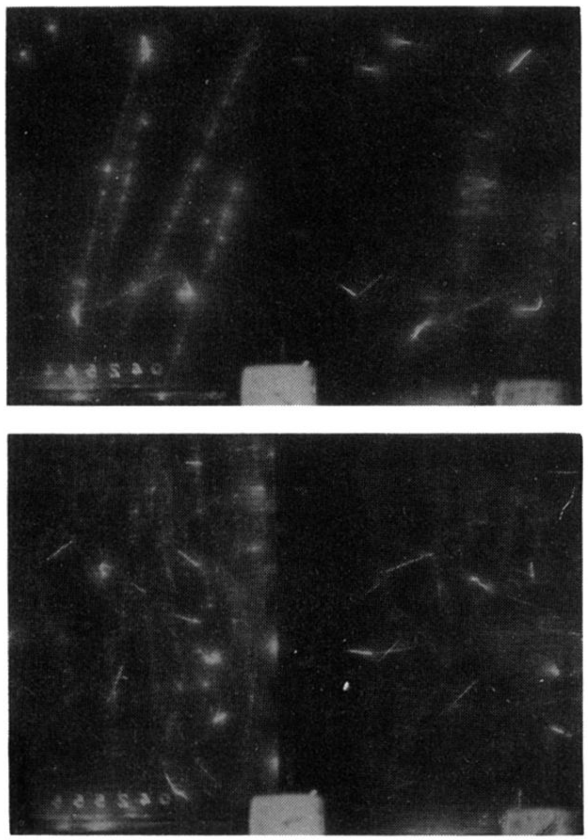

FIG. 5. (a) and (b) Examples of streamer chamber performance in extensive air showers. Electric field line and angled views are shown.