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Atmospheric Signals Caused by Cosmic-Ray Showers

ROBERT R. WILSON
Cornell University, Ithaca, New York
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It is suggested that large cosmic-ray showers can be detected by the electrical signal produced when the ionization of the shower nullifies the electric field of the earth. The signal should have two components, a very short but small signal due to the motion of free electrons, and a slow but possibly large component due to the motion of the ions. The energy of the signal is stored in the earth's electrical field until it is released by the ionization. An estimate is made of the size and duration of the signals which indicates that they may be detectable, especially in the case of the slow signal which may have a time of rise of the order of a fraction of a second.

AN electric field of from 1 to 3 volts/cm exists at the surface of the earth and extends upwards in diminishing intensity to a height of about 10 km where it has a value of roughly 5 volts/meter. A very large cosmic-ray shower can ionize the air and hence cause this field to be nullified. A detectable electric signal should then accompany this disturbance. From another point of view we can think of the lower atmosphere as being a gigantic ionization chamber. The ionization produced by a large shower will move in the electric field of the earth and produce induction signals that may be detectable at a distance. In any case the energy of the signals comes from the electrical energy stored in the earth's field and not from the cosmic-ray shower itself.

Just as in the ionization chamber analog, there will be two distinctive signals, a very short signal characterized by the motion of the electrons before they attach, and a rather slow signal due to the ponderous movement of the positive and negative ions.

Let us consider the fast signal. Because the electric field is so very small, the mean distance of travel of an electron, $\bar{x}$, before it attaches to form an ion will also be very small. Measurements do not exist down to such small fields, but a simple calculation (see the Appendix) gives

$$\bar{x}=2\times10^{-3}E, \tag{1}$$

where E is the electric field strength in volts/cm. The velocity of the electrons for such low electric field strengths will be given roughly by

$$v=10^4E. \tag{2}$$

Thus for a field strength of one volt/cm the duration of the signal due to the motion of one electron will be a fraction of a microsecond. Since the electric field extends over a distance of the order of kilometers, the duration and shape of the pulse will depend on the propagation of the shower across the region of the electric field and this will depend on the angle with respect to the zenith and on the position, i.e., on whether the shower is approaching or receding from the observer. In most cases the approximate duration of the fast pulse should be of the order of ten microseconds, although for a shower directly approaching the observer the duration can be as short as a few tenths of a microsecond.

The magnitude of the fast component of the signal can also be estimated. The layer of air at the surface of the earth which contains the electric field is roughly one km thick which is nearly three radiation lengths. A fraction, f, about one-tenth, of the total energy, W, of a large shower will be lost in this distance. The energy appears as ionization, hence the number of ion pairs produced in the layer is

$$N=(W/w)f, \tag{3}$$

where w is the energy per ion pair which is about 30 ev. For a very large shower of 10^{20} ev, about 3×10^{17} ion pairs might be produced. If the electrons move a distance of 2×10^{-3} cm, the work done on them by the electric field is $3\times10^{+17}\times2\times10^{-3}\times1.6\times10^{-19}=10^{-4}$ joules. The source of the energy which produces this work is the energy stored in the earth's electric field. If one assumes the shower to be spread over a square area, 100 meters on a side, the stored energy for this area in a height of one km for a field of one volt/cm is about $\frac{1}{3}$ joule. Thus the average field in this area can be expected to change by $\frac{1}{2}(10^{-4}/0.3)\approx10^{-4}$ in a period of about ten μsec. If an antenna sticks up 30 m and probes the potential there, which should be of the order of several kv, then the voltage might change by about 1 volt because of a nearby very large shower, i.e., one within about 100 m. At greater distances from the shower, a smaller signal would appear. Thus we can expect it to be quite difficult to measure the fast component of ordinary showers.

The slow pulse due to the motion of the positive ions can be expected to be much larger—but perhaps more difficult to recognize because of its slowness. Let us compute how long the ions last before being lost due to recombination. The loss is given by $dn=-\alpha n_+n_-dt$, where the constant α is the coefficient of recombination. If α is constant with time (which it isn't) and if $n_+=n_-$, we are led to the expression

$$n=n_0/(1+n_0\alpha t). \tag{4}$$

Now α for air is roughly 2×10^{-6}. If we assume, as before, that 3×10^{17} ion pairs are formed because of a shower of 10^{20} ev and in an average area 100 m on a side and in a height of 1 km, the average density is

$3\times 10^{17}/10^8\times 10^5 \approx 3\times 10^4$ ions/cm^3. For this density to be reduced by a factor of three, i.e., $n_0/n=3$, requires a time of some minutes.

The mobility of an ion in air is of the order of 2 cm/sec per volt/cm. Hence the ions will travel about a meter before recombining. The work done on these ions will be much greater than on the electrons, i.e., in the ratio $10^2/2\times 10^{-3}=5\times 10^4$, and taking again a very large shower of 10^{20} ev, we get 5 joules for the work done on the ions were the electric field to remain constant. But we saw that only about 0.3 joule was stored in the earth's field, consequently we conclude that the ionic motion will completely discharge the field of the earth in the vicinity of a large shower.

A shower of 10^{18} ev, will produce roughly 3×10^{15} ion pairs in the last kilometer of the atmosphere. The work done on these ions by a field of roughly 1 volt/cm as they travel one meter will be

$$2\times 3\ 10^{15}\times 100\times 1\times 1.6\times 10^{-19}\approx 0.1 \text{ joule},$$

which is still comparable to the energy stored in the field. Thus it seems possible that showers of much lower energy would be quite detectable.

Now actually the shower is not uniformly spread over the 100-meter distance but is sharply peaked about the core of the shower. The distribution is given by Molière,[1] and an approximation to his result similar to that given by Euler and Wergeland[1] is

$$N(r)=(\text{const}/r)e^{-r/r_0}. \tag{5}$$

According to Cocconi,[2] half the particles fall within a radius of 80 meters, which allows us to evaluate r_0 to be 115 meters. The ionization density is then given by (5) if we make the constant$=fW/2\pi r_0 w$.

With such a peaked distribution, what will happen is that the earth's field will be nullified in the core of the shower in a very short time because the density of ionization is so great there. At greater distances, the nullification will take longer because the fewer ions produced there must move a greater distance in order to dissipate the energy of the field. Eventually a distance will be reached where the ions will recombine before appreciably altering the field. Thus the character of the electrical signal received at a given point will depend both in time and magnitude on the position of the observer relative to the core of the shower.

We could describe the signal in detail by computing an equivalent distribution of dipoles to describe the earth's field and then by computing the rate that these dipoles are dissipated by the ion distribution given by (5).

Without going through such a complex calculation, we can see that even the "slow" signal will be characterized by a rather sharp front due to the neutralization of the field near the core and that then the signal will become slower and slower as the ionization in the outer edges of the shower moves. In a large shower, the front of the signal will be relatively faster than for a smaller shower. The rise time of the first part of the signal due to the positive-ion motion can be of the order of seconds or less depending on the size of the shower, but then it can continue to rise for as much as a minute.

By the use of multiple antennas, and especially if the fast signals are detectable, it should be quite possible to locate the position and intensity of large showers in fair weather.

APPENDIX

The mean free drift distance, $\bar{x}$, of an electron before attaching will be given, following Loeb,[3] by

$$x=\frac{\lambda}{c}\left(\frac{1}{h}\right)kE, \tag{6}$$

where λ/c is the mean time per collision, i.e., mean free path divided by average speed, $1/h$ is the number of collisions before attaching, and k is the electron mobility in the electric field E. Now k is roughly given by

$$k=\tfrac{1}{2}(e/m)(\lambda/c), \tag{7}$$

hence

$$\bar{x}=(m/e)(k^2/h)E. \tag{8}$$

At very low values of E we can expect the electronic velocities to be constant and hence that h and k be constant. Bradbury's values of k and h as given by Loeb[3] tend toward constant values at very low E/p. Extrapolation to zero E/p, gives, very roughly $k=10^4E$ and $h=6\times 10^{-5}$. Substituting in Eq. (8), we get

$$\bar{x}=2\times 10^{-3}E. \tag{9}$$

[1] G. Molière, *Cosmic Radiation*, edited by W. Heisenberg (Dover Publications, New York, 1946).

[2] G. Cocconi (private communication). See also Cocconi, Tongiorgi, and Greisen, Phys. Rev. **76**, 1020 (1949).

[3] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939).