Volume 7 OCTOBER, 1936 Number 10

PHYSICS

A Journal of General and Applied Physics

Photographic Study of Lightning

E. J. WORKMAN, *University of New Mexico,*
AND
J. W. BEAMS AND L. B. SNODDY, *University of Virginia*
(Received July 17, 1936)

Photographs of lightning taken with rotating film cameras near Albuquerque, New Mexico, in the summer of 1935 show three different types of electrical breakdown. In the first type the first flash starts at the cloud, proceeds about 1 km and stops abruptly in air. This was followed in 0.008 sec. by a second flash traversing the same path but extending it about 0.22 km. The third similar flash 0.01 sec. later extended the path 0.5 km. The fourth flash extended the path clear to earth 0.0098 sec. later. The second type showed the well-known "leader" type of breakdown of Schonland and others. The third type of breakdown consisted of only the main violent discharge between cloud and earth. The results are briefly discussed and a new possible mechanism for lightning breakdown pointed out.

THE phenomenon of lightning is now generally recognized as an important factor in many different geophysical problems.[1–3] For example, on the average there occur about 100 lightning flashes on the earth per second, the equivalent steady current of which amounts to about 2000 amperes.[3,4] Also the maximum current and potential of the flash may reach 250,000 amperes and 10^9 volts, respectively.[1,2,3,5] Therefore, it is clear that its influence on such phenomena as atmospherics[6–9] or "radio static," ionization in the earth's atmosphere,[2,3] the maintenance of the earth's negative and upper air's positive charge[3] or the mechanism of the thunderstorm[1,2] itself is important. C. T. R. Wilson has likened the thunderstorm to an immense electrostatic machine and the intercloud lightning to the sparks between its poles. Usually the positive pole of this huge machine is in the upper and the negative pole in the lower part of the cloud[10] although it is not impossible that this may be reversed in very rare cases. Also a very high voltage is usually attained between the earth and one or both poles of the cloud. This gives rise to the lightning flash between cloud and earth. In general the intercloud flashes are more abundant than those between cloud and earth. Measurements by a number of observers[1–3] agree that the average electrical field at the instant of electrical breakdown is of the order of 10,000 volts/cm instead of 30,000 volts/cm required in the case of the electrical spark.

The work reported here was undertaken with a view of securing data which, together with that already obtained by others[11–14] on various

[1] Humphreys, *Physics of the Air*, second edition, McGraw-Hill (1929).
[2] C. T. R. Wilson, Phil. Trans. Roy. Soc. **A221**, 73 (1921).
[3] Schonland, *Atmospheric Electricity* (Methuen and Co., 1932).
[4] Brookes, Meteorological Office Geophysical Memoir No. 23 (1925).
[5] Peek, J. Frank. Inst. **197**, 40 (1924).
[6] Watt and Appleton, Proc. Roy. Soc. **A103**, 84 (1923); Appleton, Watt and Herd, Proc. Roy. Soc. **A114**, 376 (1927).
[7] Norinder, J. Frank. Inst. **220**, 69 (1935); **221**, 585 (1936).
[8] Schonland, South African J. Sci. **32**, 24 (1935).
[9] Rao, Nature **136**, 683 (1935).
[10] Schonland, Proc. Roy. Soc. **A118**, 233 (1928).
[11] Schonland and Collins, Proc. Roy. Soc. **A143**, 654 (1934); Schonland, Malan and Collins, Proc. Roy. Soc. **A152**, 595 (1935).
[12] Walter, Ann. d. Physik **10**, 393 (1903); Physik. Zeits. **19**, 273 (1928).
[13] McEachron, Elect. J. **31**, 251 (1934).
[14] Boys, Nature **118**, 749 (1926); **122**, 310 (1928).

parts of the earth, should throw light on the general mechanism of lightning breakdown itself.

This first report will describe photographic observations made near Albuquerque, New Mexico, in the summer of 1935. Albuquerque has an altitude of about 5200 ft. and an abundance of night lightning particularly suited to photography because of the clear atmosphere and absence of obscuring rain, clouds, etc.

Apparatus and Results

Three cameras were used—the first with stationary photographic film, the second with film moving 80 cm/sec. and the third with film moving 850 cm/sec. The moving film cameras were of the usual type with lens stationary and film mounted on a rotating drum. For the faster camera the film was mounted on the inside of the "drum" to prevent mechanical distortion. The rotating drums were driven by hand and their speed could be held constant to better than ten percent. The lenses were achromatic and of excellent quality and the films were Eastman supersensitive panchromatic. The distance to the cloud was determined by measuring the time interval between the lightning and thunder with a stop watch and dividing this by the velocity of sound.

Fig. 1 shows a photograph taken on the film moving 80 cm/sec. in the direction indicated by the arrow F. M. The discharge was 4.5 miles away and its to talprojected two-dimensional path from cloud to earth was 1.12 miles or 1.8 km. If we follow Schonland and others in adding approximately 30 percent to this to get the length of the tortuous three-dimensional track, the total length of the discharge was about 1.5 miles or 2.4 km. It will be noted that the first flash extended only 0.98 km and ended abruptly in the air. This was followed 0.008 sec. later by a second flash traversing the same path but extending to 1.2 km and again ending abruptly in the air. The third flash occurred 0.01 sec. later and extended the path to approximately 1.7 km, while the fourth flash followed the path blazed by the others in 0.009 sec. and extended all the way to the earth. Four additional flashes (not shown in Fig. 1) traversing the same path and extending all the way to earth occurred during the next 0.08 sec.

Figs. 2 and 3 show two of a series of twelve successive flashes following the same path taken on the film moving 850 cm/sec. The two flashes shown occurred 0.017 sec. apart and were successive except for a very faint flash which occurred between them. Unfortunately the distance to these flashes was not determined with very great precision so their total length can only be given as roughly 0.8 mile or 1.2 km. It will be noted that these flashes show the well-known "leader" which starts at the cloud and proceeds to earth followed by the intense return stroke from earth to cloud.[11–13] Seven of the twelve flashes showed this "leader" and the remaining five flashes were so faint that the leader was probably too faint to be recorded. The velocities (4×10^9 cm/sec.) of the two "leaders" shown were approximately the same.

Fig. 4 shows two isolated flashes which occurred three miles away. The flashes were 0.52 mile in length and have a time separation of 8×10^{-5} sec. These flashes apparently ended the storm. On the original negative the first flash shows a possible indication of a leader which is too faint to reproduce.

Fig. 5 shows a flash taken on the film moving 850 cm/sec. It was two miles away and 1.2 miles in length as projected in two dimensions. No leader could be observed on the film although the photographic conditions were particularly favorable to record it had it existed. The original negative shows the flash repeated three times at intervals of roughly 1.2×10^{-4} sec., 1.3×10^{-4} sec. and 2.4×10^{-4} sec., respectively. This flash, together with that shown in Fig. 4, represents a type which occasionally occurs in this region. The discharges usually take place, often quite unexpectedly, after the storm has run its course and the sky is generally overcast thus causing a light rain. The thunder is cannon-like.

Discussion of Results

The three distinctly different types of the initiation of lightning shown in the above pictures strongly indicate that perhaps different mechanisms of lightning breakdown exist, depending upon the physical properties of the cloud or storm. Whatever may be the correct mechanism for the generation of high voltage by the thunderstorm,[1, 2, 15, 16] it is known that the conditions of the path just before the lightning flash are variable. For example, the rain may be intense or slight. The wind may be high or may not exist at all. Brush discharges may or may not be present, etc. As a result, it seems logical to expect the initiation process of different flashes to be variable. Our observations illustrated in Figs. 2 and 3 confirm the important work of Schonland[11] and others[12] and is in general agreement with Schonland's conclusion that a leader precedes the main stroke in a majority of cases. Also one of our pictures, which unfortunately was not suitable for reproduction, showed the "stepped" leader recently discovered by Schonland, Malan and Collins. No attempt at this time will be made to apply the current theories[11, 15, 17, 18] of lightning breakdown to our results, but it may be of interest to note the striking resemblance of the propagation of this type of lightning discharge to the propagation of luminosity in long discharge tubes observed by one of us.[19] If an impulsive voltage is applied to one end of a long discharge tube while the other end is grounded, both the luminosity and potential wave traverse the tube from the high voltage electrode to the grounded electrode with a definite finite velocity regardless of the sign of the applied voltage.[19, 20] The velocity of the luminosity and potential wave in a discharge tube depends upon such factors as the applied voltage and pressure of gas but does not greatly differ from that of the "leader." It was pointed out[19] that this propagation of luminosity in the discharge tube could result from a "moving" space charge so that the same mechanism may also exist in the case of the lightning flash. It is also interesting to observe that the velocity of propagation is increased in both the discharge tube and in the lightning flash[11] by a weak ionization before the discharge. As the two flashes Figs. 2 and 3 are members of a number of successive strokes, the high velocity observed for the leaders is thus accounted for by the weak ionization existing before the stroke.

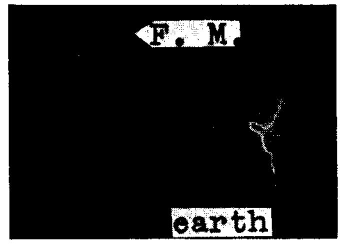

FIG. 1.

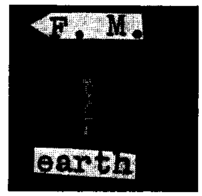

FIG. 2.

FIG. 3.

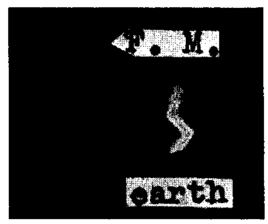

FIG. 4.

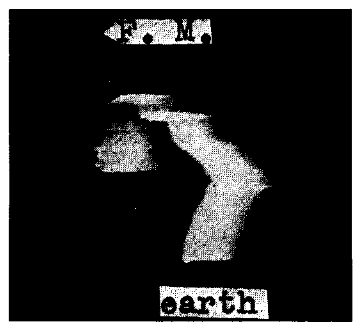

FIG. 5.

FIGS. 1, 2, 3, 4, 5. Photographs of lightning on moving film. Film motion is to the left.

The flash in Fig. 5 may have been initiated by a different mechanism as no leader was observed. Unfortunately the polarity of this flash was not obtained so that nothing is known concerning the polarity of the cloud. However, it is possible that an intercloud discharge first occurred which impressed a voltage much above the usual lightning breakdown voltage of 10,000 volts/cm between

[15] Simpson, Proc. Roy. Soc. **A114**, 376 (1927); **A111**, 56 (1926); Phil. Trans. Roy. Soc. **A209** 397, (1909).
[16] Gunn, Terr. Mag. and Atmos. Elect., March, 1935.
[17] Dorsey, J. Frank. Inst. **20**, 484 (1926).
[18] Cravatt and Loeb, Phys. Rev. **36**, 997 (1930).
[19] Beams, Phys. Rev. **36**, 997 (1930).
[20] Snoddy, Beams and Dietrich, Phys. Rev. **50**, 469 (1936).

cloud and ground. This high voltage might account for the non observance of the leader. On the other hand if Dorsey and Schonland's "electron avalanche" theory is correct, the leader would perhaps not exist when the cloud is positive with respect to ground.

The flash shown in Fig. 1 represents a type of breakdown that as far as we know has not been previously recorded. The times between the first three flashes which end in the air are too long to make it possible to associate them with leaders. Also their intensity and appearance indicates that each is a type of "main" stroke. As this picture was made with the slow camera (80 cm/sec. film speed), the leader could probably not have been clearly resolved if it existed. The fact that the first three flashes did not reach the earth suggests that the voltage was interrupted before the flash reached the earth. Most charged clouds extend over a wide space (order of kilometers[2]). Therefore it is possible that the resistance within the cloud was so great that energy could not be fed into that part of the cloud where the flash was initiated fast enough to keep the flash going. On this hypothesis the flash would stop until the potential built up and would then discharge again just as observed. When the flash finally reached the earth the high voltage no longer existed across the length of the flash because of the comparatively low resistance of the path but was applied between the parts of the cloud. Consequently either spark or glow discharges were probably formed within the cloud. These immediately lowered its internal resistance and permitted the violent fourth flash. The existence of these spark and glow discharges may account for the fogging of the original film near the beginning of the flash.

We wish to point out a mechanism of lightning breakdown which is able to account for many of our results. It is based upon the principle of cascaded spark gaps as used in the spark gap transmission line developed at the University of Virginia. This consists of a number of spark gaps connected in series in the form of a transmission line with one end grounded. When an impulsive voltage more than necessary to break down the first gap but not great enough to break down all of them is applied to the other end, the first gap breaks down followed by all the others in succession. In the case of the lightning flash the raindrops, groups of ions or other conducting regions in the air act as the electrodes for the "spark gap line."

The impulsive potential could easily be applied by a local spark or discharge in or close to the cloud since it is easy to see how local fields near the cloud may reach 30,000 volts/cm when the average field is 10,000 volts/cm. According to Humphreys[1] there is good reason for believing that conducting regions considerably larger than the raindrop may frequently exist in a thunderstorm. Also Zeleny[21] and others[22, 23] have shown that a drop of water in a field of 10,000 volts may produce a brush discharge and thus make fairly large regions of the air conducting.

In the actual case the charges on these conducting regions as well as their capacities to surrounding regions would of course be variable, but for the purpose of a simple illustration let us assume the capacities equal and the charges zero. If the capacity of each conducting region to the other similar conducting regions in the direction of the field is C_1 and its capacity to those perpendicular to the field is C_2 and if the impulsive potential applied by a spark in the cloud is V, it can easily be shown that the potential V_1 between the first two similar conducting regions nearest the cloud is given by

$$V_1 = V\left[\frac{C_2/2+(C_2^2/4+C_1C_2)^{\frac{1}{2}}}{C_1+C_2/2+(C_2^2/4+C_1C_2)^{\frac{1}{2}}}\right]$$

and V_k between the K and $(K+1)$st similar conducting regions in the direction of the field is

$$V_k = V\left[\frac{C_2/2+(C_2^2/4+C_1C_2)^{\frac{1}{2}}}{C_1+C_2/2+(C_2^2/4+C_1C_2)^{\frac{1}{2}}}\right]^k.$$

If the conducting regions are randomly spaced (as would be approximately true if they were raindrops themselves) on the average C_2 should be roughly twice C_1, but assuming them equal for the purpose of a rough calculation $V_1 = 0.6V$ while $V_k = (0.6)^k V$. In other words, most of V would be applied between the first two conducting regions until the gap separating them broke

[21] Zeleny, Phys. Rev. **3**, 69 (1914); **16**, 108 (1920); J. Frank. Inst. **219**, 659 (1935).
[22] Macky, Proc. Roy. Soc. **A133**, 565 (1931).
[23] Tonks, J. Frank. Inst. **221**, 613 (1936).

down. This would apply the potential V_1 between the second and third conducting regions until the gap separating them broke down, etc. As a result the lightning flash could take place when the voltage of the cloud was much less (easily at an average field of 10,000 volts/cm) than the normal sparking voltage. Also the luminosity would normally start at the cloud and move toward the ground. In fact if the conducting regions are large, the so-called time lag of the spark gap breakdown should hold up the discharge momentarily at each conducting region, which would naturally account for the stepped leaders discovered by Schonland[11] and observed in our work.

This investigation is being continued during the summer of 1936 with improved apparatus with the hope of collecting more precise and a wider range of data.

We are much indebted to the Virginia Academy of Science and the Research Committee of the University of Virginia for grants which made this work possible. Also we wish to thank Mr. E. L. Hardy, New Mexico Section Director, U. S. Weather Bureau, for continued cooperation and interest in the work.