

The Physical Parameters of Lightning and the Techniques by Which They Are Measured

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INTRODUCTION

ONE of the earliest attempts at a physical explanation of the lightning discharge was due to Aristotle.

“Let us now explain thunder and lightning. . . . As we have said, there are two kinds of exhalation, moist and dry; and their combination (air) contains both potentially. It condenses into clouds . . . and the condensation of clouds is thicker toward their farther limit. . . . But any of the dry exhalation that gets trapped when the air is in the process of cooling is forcibly ejected as the clouds condense and in its course strikes the surrounding clouds; and the noise caused by the impact is what we call thunder. . . . As a rule, the ejected wind burns with a fine and gentle fire, and it is then what we call lightning. . . . Lightning is produced after the impact and so later than thunder, but appears to us to precede it because we see the flash before we hear the noise.” (Aristotle, 384BC-320BC, *Meteorologica*, Translated by H. D. P. Lee, Harvard University Press, 1951).

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We know today that lightning is nothing more than a giant electric spark and that audible thunder is the noise created by the spark as its hot gases expand against the ambient atmosphere. Obvious as these facts may seem now, a period of about 2000 years elapsed from the time of Aristotle until the time that evidence was produced to show that lightning was indeed electrical. In fact as recently as the middle ages, church bells were rung in an effort to disperse lightning. There are many recorded instances of the electrocution by lightning of church-bell ringers as they performed their appointed task. It was Benjamin Franklin, 200 years ago, who showed that thunderclouds are electrically charged (he showed that the bottoms of typical thunderclouds were negatively charged) and deduced that lightning is a long spark which discharges the clouds. As a part of his work, Franklin invented the lightning rod still used today in essentially unaltered form. Franklin was the sole forerunner of the modern lightning research which began about 1900.

Modern scientific techniques have been used to measure most of the physical parameters of lightning. In particular there is data available concerning (1) the light output and velocity of propagation of lightning's various luminous processes, (2) the electrical properties of the channel including current, charge, energy, and power inputs, (3) the electric and magnetic fields generated by the discharge, (4) the optical spectrum and channel thermodynamic properties derived from it including channel temperature, electron density, and pressure, (5) the acoustic output of the discharge.

Most of the available information relates to cloud-to-ground lightning because it is the most amenable to photographic studies. This paper will be primarily concerned with the usual cloud-to-ground discharge which begins in the cloud and lowers negative charge to earth. Only brief space will be devoted to the more commonly occurring but less well understood intracloud discharge and to such rarer types of lightning as ground-to-cloud, cloud-to-ground lowering positive charge, and intercloud.

The primary purposes of this paper are to convey to the reader some feeling for the history of lightning research, a general idea of how lightning "works", some quantitative data regarding its physical

parameters, and information on how these are measured. No attempt is made at completeness. The material is organized into five main sections, one for each of the five general diagnostic techniques (photography, electric and magnetic field measurements, current measurements, spectroscopy, and thunder measurements) used to study lightning. For a more detailed introduction to lightning the reader is referred to the books by Malan (1963), Schonland (1964), and Uman (1969a, 1971). In the present paper specific literature will only be cited if it has not been referenced and discussed in more detail in Uman (1969a), or if it accompanies a presentation of data or a drawing.

LIGHTNING PHOTOGRAPHY

A cloud-to-ground lightning discharge is made up of one or more intermittent partial discharges. The total discharge, whose time duration is of the order of 0.2 sec, is called a *flash*; each component discharge, whose luminous phase is measured in tenths of milliseconds, is called a *stroke*. There are usually three or four strokes per flash, the strokes being separated by tens of milliseconds. Often lightning as observed by the eye appears to flicker. In these cases the eye is discerning the individual strokes which make up a flash. Cloud-to-ground discharges normally lower tens of coulombs of negative charge from the N-region of the cloud (Fig. 1) to the ground. Each lightning stroke begins with a weakly luminous pre-discharge, the *leader* process, which propagates from cloud-to-ground and which is followed immediately by a very luminous return stroke which propagates from ground-to-cloud.

In order to study photographically the development of the lightning discharge, it is necessary to use a camera which can time-resolve the luminous propagating phenomena which comprise the flash. In such a camera there must be relative motion between the film and the lens. The earliest studies of this sort (published in the 1890's) consisted of moving ordinary cameras back and forth in the horizontal plane with their shutters open while lightning was occurring. These studies identified the individual strokes in a flash and the leader pre-

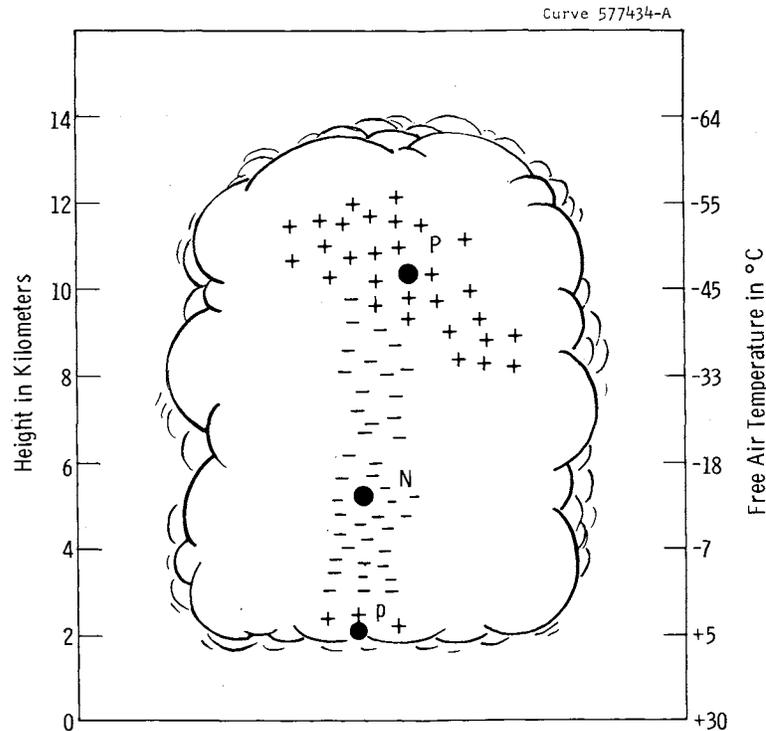


FIG. 1. Probable distribution of the thundercloud charges, P, N and p for a South African thundercloud according to Malan (1963). Solid black circles indicate locations of effective point charges, typically $P = +40$ coul., $N = -40$ coul., and $p = +10$ coul., to give observed electric field intensity in the vicinity of the thundercloud.

ceeding the first stroke. In the early 20th century C. V. Boys invented the camera which now carries his name and which was to provide almost all of the photographic information on cloud-to-ground lightning that is at present available. A drawing of the Boys camera and a description of its operation is given in Figure 2.

On the basis of Boys camera and electric field measurements begun primarily in South Africa in the 1930's and continued to the present at various observatories throughout the world the following picture of cloud-to-ground lightning has been assembled.

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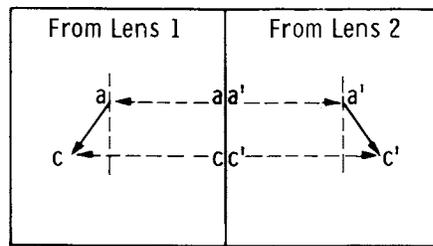
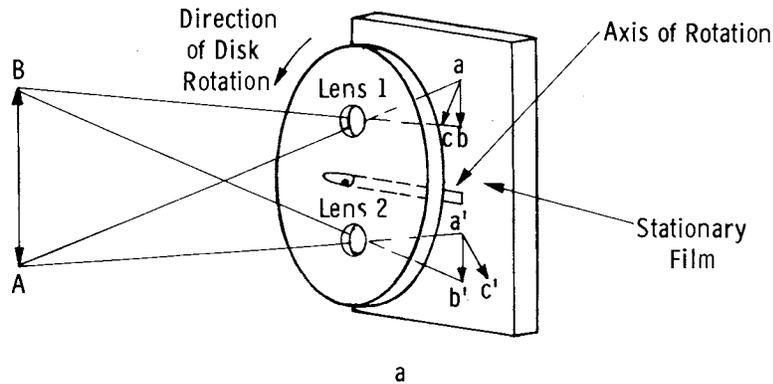


FIG. 2. (a) Diagram of Boys camera with moving lenses and stationary film. Luminosity progressing from A to B leaves the image ab ($a'b'$) when the disk carrying the lenses is stationary and ac ($a'c'$) when the disk is rotating. (b) By placing the two photographic images side by side, the time of propagation of luminosity from A to B, $(cc' - aa')/2v$, where v is the velocity of each lens, may be determined. Drawing adapted from Uman (1969a).

The usual cloud-to-ground discharge probably begins as a local discharge between the p-charge region in the cloud base and the N-charge region above it (Figs. 1 and 3). This discharge frees electrons in the N-region previously immobilized by attachment to water or ice particles. The free electrons overrun the p-region, neutralizing its small positive charge, and then continue their trip toward ground.

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The vehicle for moving the negative charge to earth is the *stepped leader*. Exactly how the stepped leader works is not understood. What is known is that it moves from cloud to ground in rapid luminous steps about 50 m long. In Figures 3 and 4 the luminous steps appear as darkened tips on the less-luminous leader channel which extends upward into the cloud. Each leader step occurs in less than a microsecond. The time between steps is about 50 μ sec. Nega-

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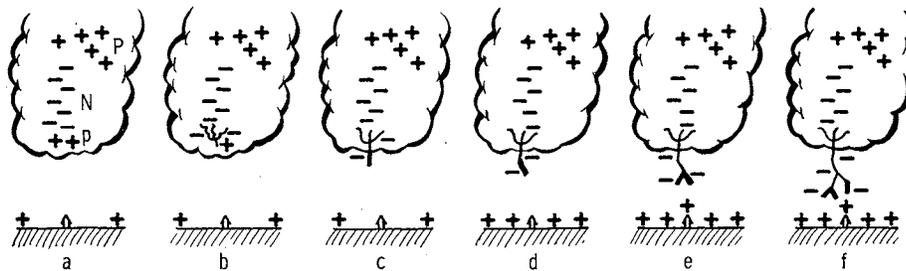


FIG. 3. Stepped leader initiation and propagation. (a) Cloud charge distribution just prior to p-N discharge. (b) p-N discharge. (c)-(f) Stepped leader moving toward ground in 50 m steps. Time between steps is about 50 μ sec. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).

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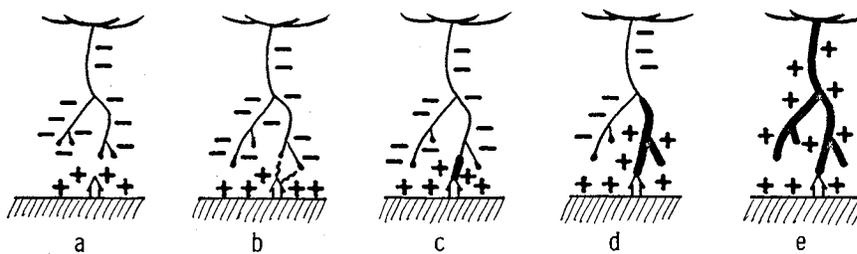


FIG. 4. Return stroke initiation and propagation. (a) Final stages of stepped leader descent. (b) Initiation of upward-moving discharges to meet downward-moving leader. (c)-(e) Return stroke propagation from ground to cloud. Return stroke propagation time is about 10 μ sec; propagation is continuous. Scale of drawing is distorted. Adapted from Uman (1971).

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tive charge is continuously lowered from the N-region of the cloud into the leader channel. The average velocity of the stepped leader during its trip toward ground is about 10^5 m/sec with the result that the trip between cloud and ground takes about 20 msec. A typical stepped leader has about 5 coulombs of negative charge distributed over its length when it is near ground. To establish this charge on the leader channel an average current of about 100 or 200 amperes must flow during the whole leader process. The pulsed currents which flow at the time of the leader steps probably have a peak current of about 1000 amperes. The luminous diameter of the stepped leader has been measured photographically to be between 1 and 10 m. It is thought that most of the stepped-leader current flows down a narrow conducting core less than a few centimeters in diameter at the center of the observed leader. The large photographed diameter is probably due to a luminous electrical corona surrounding the conducting core.

When the stepped leader is near ground, its relatively large negative charge induces large amounts of positive charge on the earth beneath it and especially on objects projecting above the earth's surface (Fig. 4). Since opposite charges attract each other, the large positive charge attempts to join the large negative charge, and in doing so initiates upward-going discharges. One of these upward-going discharges contacts the downward-moving leader and thereby determines the lightning strike-point. When the leader is attached to ground, negative charges at the bottom of the channel move violently to ground, causing large currents to flow at ground and causing the channel near ground to become very luminous. Since electrical signals (or any signals, for that matter) have a maximum speed of 3×10^8 m/sec—the speed of light—the leader channel above ground has no way of knowing for a short time that the leader bottom has touched ground and has become highly luminous. The channel luminosity (the visible effect of the return stroke) propagates continuously up the channel and out the channel branches at a velocity somewhere between 1/2 and 1/10 the speed of light, as shown in Figure 4. The trip between ground and cloud takes about 100 μ sec. As the return stroke luminosity moves upward so also does the region of

high current. When the leader initially touches ground, copious numbers of electrons flow to ground from the channel base. As the return stroke moves upward, large numbers of electrons flow at greater and greater heights. Electrons at all points in the channel *always move downward* even though the region of high current and high luminosity moves upward. Eventually, in some milliseconds, the coulombs of charge which were on the leader channel have all flowed into the ground. Since the return stroke channel is a good conductor and is tied to the ground, it will become positively charged like the ground in response to the negative charge in the lower part of the cloud.

It is the return stroke that produces the bright channel of high temperature that we see. The eye is not fast enough to resolve the propagation of the return stroke and it seems as if all points on the channel become bright simultaneously. The reason that we do not visually detect the stepped leader preceding a first return stroke is because the eye cannot resolve the time between when the weakly luminous leader is formed and the bright return stroke illuminates the leader channel.

After the stroke current has ceased to flow, the lightning flash may be ended, in which case the discharge is called a single-stroke flash. As noted previously, most flashes contain three or four strokes, typically separated by gaps of 40 or 50 msec. Strokes subsequent to the first are initiated only if additional charge is made available to the top of the previous stroke channel less than about 100 msec after current has stopped flowing in the previous stroke. Additional charge can be made available to the channel top by the action of electrical discharges (so called *K-streamers* and *J-streamers*) which move upward and outward from the top of the previous return stroke into untapped areas of the N-charge region of the cloud (Fig. 5). When this additional charge is available, a continuous (as opposed to stepped) leader, known as a *dart leader*, moves down the defunct return stroke channel again depositing negative charge from the N-region along the channel length. The dart leader thus sets the stage for the second (or any subsequent) return stroke. The dart leader's earthward trip (Fig. 6) takes a few milliseconds. Because it occurs

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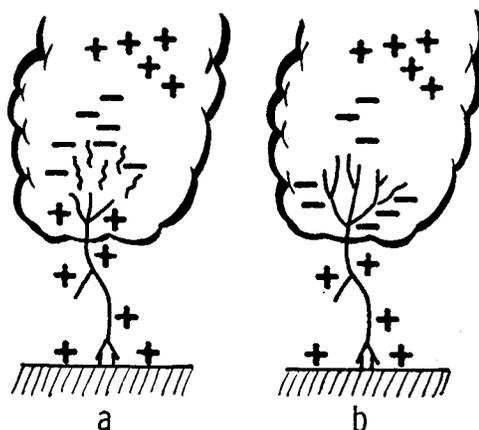


FIG. 5. K-streamers and J-streamers making more negative charge available to the channel top during the 50 milliseconds or so following the cessation of current flow in the first return stroke. Scale of drawing is distorted. Adapted from Uman, (1971.)

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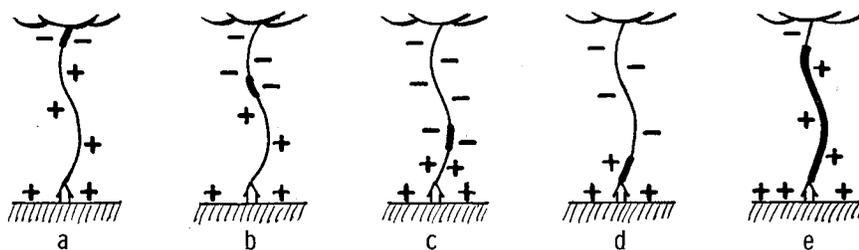


FIG. 6. Dart leader and subsequent return stroke. (a)-(c) Dart leader deposits negative charge on defunct first-stroke channel during its thousandth-of-a-second trip to ground. (d)-(e) Subsequent return stroke propagates from ground to cloud in about 100 μ sec. Scale of drawing is distorted. Adapted from Uman, (1971.)

so close in time to the return stroke, it is not seen by the eye. To special cameras it appears as a luminous section of channel about 50 m long which travels smoothly earthward at about 10^6 m/sec. The dart leader generally deposits somewhat less charge along its path

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than does the stepped leader, with the result that subsequent return strokes generally lower less charge to ground and have smaller currents than first strokes.

The first stroke in a flash is usually strongly branched downward because the stepped leader is strongly branched. Dart leaders generally follow only the main channel of the previous stroke and hence subsequent strokes show little branching.

The time between strokes which follow the same path can be tenths of a second if a "continuing current" flows in the channel between strokes. Apparently, the channel is ripe for a dart leader only after the continuing current has terminated. While the leader-return stroke process transfers charge to ground in two steps (charge is put on the leader channel and then is discharged to ground), the continuing current represents a relatively steady charge flow between the N-region and ground. Continuing currents are apparently the agents for setting lightning fires in forest fuels. These currents are further discussed in the "CURRENTS" section.

Thus far in this section we have discussed the usual stepped leader which lowers negative charge between the cloud and the earth. Occasionally downward-moving stepped leaders are photographed that lower positive charge. Currents due to the resulting "positive" return strokes have been measured directly during discharges to instrumented towers. Positive strokes are probably initiated between the P-charge region of the cloud and ground when strong winds blow the cloud such that the P-region is brought relatively close to a mountain side or to the earth's surface. Positive discharges rarely consist of more than one stroke.

Stepped leaders that move upward toward the cloud are commonly initiated from tall structures such as the Empire State Building or towers or mountains. Upward-moving leaders can carry either positive or negative charge and do not initiate return strokes when they reach the cloud. Typically the leader current measured at ground merges smoothly into a more or less continuous current of a few hundred amperes.

Intracloud discharges have a duration of the order of 0.2 sec (as do ground flashes), during which time a continuous low luminosity is

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photographed in the cloud. It is thought that during this time a propagating leader bridges the gap between the two main charge centers. Superposed on the continuous luminosity are relatively bright luminous pulses which are probably relatively weak return strokes that occur when the propagating leader contacts a pocket of charge of opposite polarity to that of the leader.

ELECTRIC AND MAGNETIC FIELD MEASUREMENTS

The presence and motion of electrical charges in the atmosphere can be monitored by measurement of the electric and magnetic fields produced by those charges. C. T. R. Wilson in two classic papers published between 1910 and 1920 showed how the amount of charge lowered from cloud to ground by a lightning flash could be determined from a measurement of the change in the electric field many kilometers away. Wilson's data yielded 10 to 50 coulombs of negative charge per flash, values which agree well with more recent measurements. On the basis of his electric field measurements Wilson suggested that the charge distribution in a thundercloud was primarily in the form of a vertical dipole with the positive charge on top. This main charge structure was subsequently confirmed by a number of investigators (for example, see Fig. 1) although there is still considerable controversy concerning the exact magnitude of the cloud charges due to the difficulty of measuring the fields of those charges in the presence of the fields of the atmospheric charges which surround the cloud (Brown et al. 1971). The measurement of lightning's electric fields and the deduction of the charges and currents (charge motion) causing them is at present a very active field of study. The basic features of the electric field changes during all phases of the lightning flash were identified by B. F. J. Schonland, D. J. Malan and coworkers in a study carried out in South Africa from the 1930's to 1950's. Recently, due to work carried out at the New Mexico Institute of Mines and Technology, the charge lowered per lightning stroke and the charge transferred during the time between strokes have been accurately measured. Two electric field studies in progress at present in the United States have as their aims (1) the location of the charge

centers which feed the lightning, and (2) the determination of currents in the lightning channel on a microsecond time scale.

Measurements of the magnetic fields of lightning have been made primarily by H. Norinder and his coworkers in Sweden in a study which extended from the 1930's thru the 1950's. The lightning currents calculated from their magnetic field measurements are suspect due to the inadequate theory used (Uman and McLain 1969).

Lightning electric fields are measured by an antenna coupled to suitable electronics. (In C. T. R. Wilson's original experiment the antenna was coupled to a gold leaf electrometer.) The system is generally simpler than but similar to an ordinary radio receiver. Nearly everyone has heard the lightning-caused static on AM radios. The lightning-system antennae are sometimes vertical whips exactly like a car antenna, but more often are flat plates oriented parallel to the ground and raised a meter or so above the ground. The disadvantage of the vertical whip for studying close lightning is that it may go into corona when a storm is overhead. Electric field waveforms have been measured with systems whose bandpasses extend from near dc to over a megahertz. Narrow band studies have been done in practically all regions of the radio spectrum.

The antenna generally used for measuring lightning magnetic fields is a shielded (from electric fields) loop. The induced voltage at the output of the loop is proportional to the rate of change of magnetic field normal to the loop. This voltage is integrated electronically to obtain the magnetic field.

It is possible to express the vertical electric field intensity E_z at ground and the magnetic flux density B_Φ parallel to the ground produced by a lightning discharge to earth a distance D away, if D is much greater than the channel height H , as

$$E_z = \frac{M}{4\pi\epsilon_0 D^3} + \frac{1}{4\pi\epsilon_0 C D^2} \frac{dM}{dt} + \frac{1}{4\pi\epsilon_0 C^2 D} \frac{d^2 M}{dt^2} \quad (1)$$

$$B_\Phi = \frac{\mu_0}{4\pi D^2} \frac{dM}{dt} + \frac{\mu_0}{4\pi C D} \frac{d^2 M}{dt^2} \quad (2)$$

where the "retarded" electric dipole moment M is related to the charge density ρ along the assumed vertical channel (z -direction) by

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$$M = 2 \int_0^H \rho(z, t - \frac{D}{C}) z dz \quad (3)$$

(McLain and Uman 1971). In (1) and (2), ϵ_0 is the permittivity, μ_0 the permeability, and C the speed of light of free space. The first term on the right-hand side of (1) is called the electrostatic field term. The electrostatic field change is proportional to the charge ΔQ transferred to ground. The electrostatic field change for a total charge transfer from cloud to ground of ΔQ can be written

$$\Delta E_z = \frac{2H \Delta Q}{4\pi\epsilon_0 (H^2 + D^2)^{3/2}} \quad (4)$$

The electrostatic field is the dominant term in (1) at small values of D . The last terms on the right of (1) and of (2) are called the radiation field. The radiation field is the dominant lightning field at distances beyond about 50 or 100 km due to its $1/D$ dependence. In Figure 7 is illustrated the electric fields due to the 3 or 4 strokes in one flash at 180 km, and the 3 strokes in a flash at 5 km. For a distance of 5 km, the radiation field is dominant during the first few microseconds of the waveform due to the high-frequency content of that part of the waveform. After about 20 μs the waveform is predominately electrostatic. The electrostatic off-set caused by each stroke is proportional to the charge transferred by that stroke as indicated by (4). Further, any charge transferred to ground between return strokes or after the last return stroke (note that Fig. 7 shows only the stroke field changes) can be determined from (4), and charge motion in the cloud can be determined from expressions similar to (4). From the initial radiation peak in the close and distant waveforms as shown in Figure 7, the initial channel-current waveform can be deduced (Uman and McLain 1970).

CURRENT

The first measurement of lightning current was made by F. Pockels in the late 19th century. In 1897 he reported he had found that rock in the vicinity of several trees which had been struck by lightning were magnetized by the lightning current. On the basis of laboratory

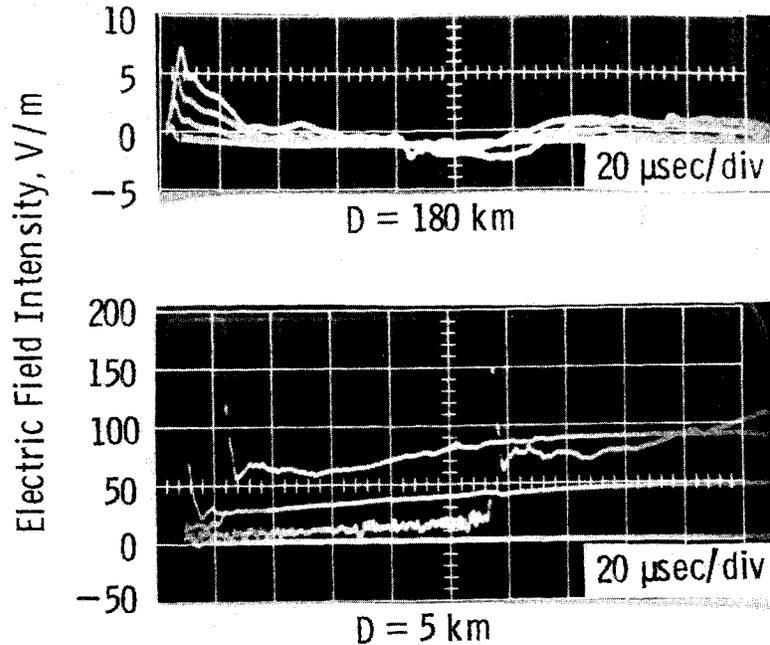


FIG. 7. The electric field intensities of the return strokes in a close and a distant multiple-stroke flash. Data taken near Pittsburgh, Pa. by R. J. Fisher and M. A. Uman.

experiments he deduced that peak currents of 5 to 10 kA were necessary to produce the observed magnetization. A few years later, Pockels placed samples of the same magnetizable natural rock (basalt) several centimeters from a lightning rod often struck by lightning and measured peak lightning currents in two flashes of 11 and 20 kA.

Pockel's peak-current measuring technique was revived in the 1930's in the form of the *magnetic link*, a piece of magnetizable material constructed in the laboratory (for example, from strips of cobalt steel). Magnetic links are still widely used today. One of the more sensational measurements made lately using links was of the peak currents in the several lightning flashes which struck the Apollo 15 launch umbilical tower in the 6 weeks prior to the lift-off for the

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moon in July 1971. One of these currents was almost 100 kA. Most of the data available at present on peak lightning currents comes from magnetic link measurements made on transmission-line towers. Data representing the highest current in each of 2721 lightning flashes is given in Table 1. The median value of peak current in this study was 15 kA, the largest current 218 kA. Other investigators have generally found median peak currents in the range 5 to 20 kA. Currents over 200 kA are occasionally reported.

For many applications (e.g., the design of certain types of lightning protection equipment) it is necessary to know not only the

TABLE 1. PEAK LIGHTNING CURRENTS AS MEASURED USING MAGNETIC LINKS.
ADAPTED FROM LEWIS AND FOUST (1945).

Range of current, Amp	No. of flashes with peak current in range	No. at or above level	Percentage at or above level
1,000- 5,000	567	2,721	100
5,001- 10,000	611	2,145	79.2
10,001- 20,000	640	1,543	56.7
20,001- 30,000	296	903	33.2
30,001- 40,000	227	607	22.3
40,001- 50,000	140	380	14.0
50,001- 60,000	80	240	8.82
60,001- 70,000	61	160	5.88
70,001- 80,000	22	99	3.64
80,001- 90,000	21	77	2.83
90,001-100,000	11	56	2.06
100,001-110,000	11	45	1.65
110,001-120,000	9	34	1.25
120,001-130,000	9	25	0.918
130,001-140,000	7	16	0.588
140,001-150,000	2	9	0.331
150,001-160,000	3	7	0.257
160,001-170,000	0	4	0.137
170,001-180,000	1	4	0.147
180,001-190,000	0	3	0.110
190,001-200,000	1	3	0.110
200,001-210,000	0	2	0.073
212,000	1	2	0.073
218,000	1	1	0.037
Total	2,721		
Maximum negative	218,000		
Maximum positive	212,000		

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peak lightning current, but also the lightning current waveshape. The most successful measurements of lightning current waveshape have been made at the Empire State Building in New York City and on towers near Lugano, Switzerland by allowing the lightning current to flow through a resistance of known value and recording the voltage across that resistance on a cathode-ray oscilloscope. Surprisingly perhaps, only a few hundred current waveforms have been recorded to present. Figure 8 shows representative currents for strokes with peak currents greater than 10 kA recorded on a tower atop Mt. San Salvatore near Lugano. In these studies first stroke risetimes were found to be of the order of 10 μ sec; subsequent stroke risetimes of the order of 1 μ sec. Leaders traveling upward from the tower to meet the downward-moving stepped leader may contribute

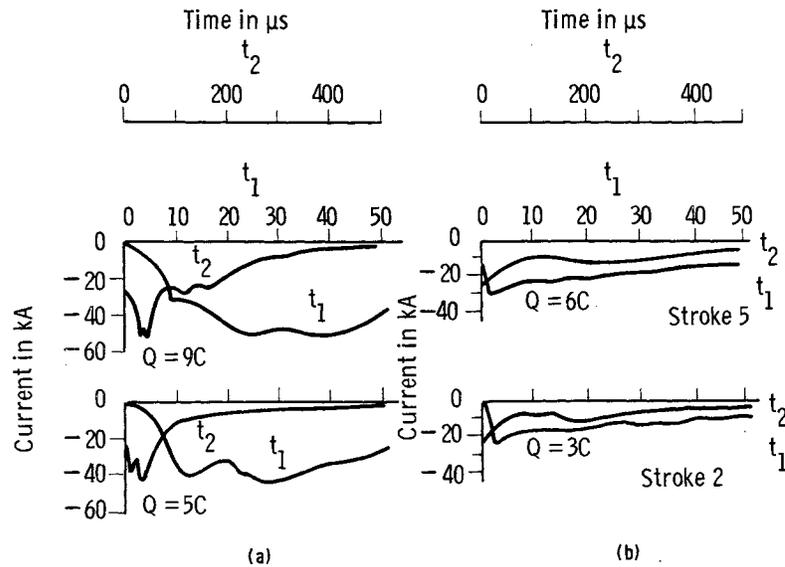


FIG. 8. Current versus time for representative lightning strokes in the class of strokes with peak currents greater than or equal to 10 kA. For each stroke, data are presented on two time scales; t_1 , fast, t_2 , slow. Charge Q is the time integral of current to 1 ms. (a) Two first strokes. (b) Two subsequent strokes. Data adapted from Berger (1967).

appreciably to the current measured at ground for a first stroke.

The median current risetime measured in the Empire State Building study was about 1 μsec , with a longest risetime of about 6 μsec . No differences were noted between first and subsequent stroke risetimes. The median time for the current to fall to half of peak value was about 30 μsec , with a maximum time of about 120 μsec . The median value of charge lowered per flash, found by integrating the current waveforms, was about 20 coulombs, in good agreement with the data derived from electric field measurements discussed in the previous section. The maximum value of charge transferred per flash was about 200 coulombs.

A significant fraction, perhaps half, of the charge transferred to ground in a typical lightning flash is due to relatively small currents which may flow during the time between strokes. This *continuing current* generally has a value of about 100 Amps and flows for about 0.1 seconds transferring about 10 coulombs of charge. It is thought to be the continuing current which causes forest fires (Fuqua et al. 1972). These currents provide a high enough temperature for a long enough time to ignite combustile materials. Alan R. Taylor, in an article reproduced in this volume, suggests that lightning produces and ignites fine-particle debris showers from the trunks of struck trees and that these "fireballs" in turn ignite material on the forest floor. The continuing currents measured directly in flashes to tall structures agree well with values determined from distant electric and magnetic field measurements.

SPECTROSCOPY

Lightning spectroscopy has been practiced for over a century. Thus as a diagnostic technique for the study of lightning, its origins predate the use of photography and of electric field, magnetic field, and current measurements. The early lightning spectroscopists were astronomers for whom the lightning was an unwelcomed light source. Interestingly, much of the modern study of the lightning spectrum has also been carried out by researchers trained in the spectroscopy of astronomical objects.

In lightning spectroscopy, the ultraviolet, visible, and infrared output of the lightning channel are decomposed in wavelength, and the salient features of the spectrum analyzed to yield the lightning temperature, electron density, and other channel properties. The spectrum is typically produced by allowing the light under study to pass thru a dispersing prism or, what is equivalent, a diffraction grating. If sunlight is passed through a prism, the light is decomposed into its spectrum. (The rainbow is the sun's spectrum produced by water droplets.) Sunlight is composed of a range of colors varying in hue continuously from red to orange to yellow to green to blue to violet. Incandescent solids (e.g., tungsten filaments) or incandescent gases at very high pressure or occupying large volumes (e.g., the sun) produce continuous spectra, that is, light which includes all colors. Luminous gases at lower pressure or occupying small volumes (e.g., the lightning channel) produce spectra with "lines" at characteristic wavelengths. A given molecule, atom, or ion is capable of emitting radiation only at specific wavelengths which are different for different kinds of particles. Each molecule, atom, or ion has its own unique radiation "signature" by which it can be positively identified. We can get a rough idea of the temperature of air by determining from the radiation emitted by the air whether it is predominantly composed of molecules, atoms, or ions. A more exact determination can be made by examining the intensities of the characteristic spectral lines from a given molecule, atom, or ion.

A spectrum (wavelength region 5500 Å to 6700 Å) from about 10 m of the lightning return stroke channel is shown in Figure 9. If the spectrum were printed in color, the 5680 Å line from singly ionized nitrogen (NII) would be green and the H_{α} line at 5653 Å would be red. The H_{α} line (Balmer Series) is emitted by hydrogen atoms present in the channel due to the high-temperature breakup of water vapor (H_2O). The H_{α} line has the useful property that its width is proportional to the electron density in the channel via the Stark effect. A lightning electron density vs. time curve derived from the width of H_{α} is shown in Figure 10. A temperature curve determined from nitrogen ion line intensities is given in Fig. 11. Once the temperature and electron density in the channel are known,

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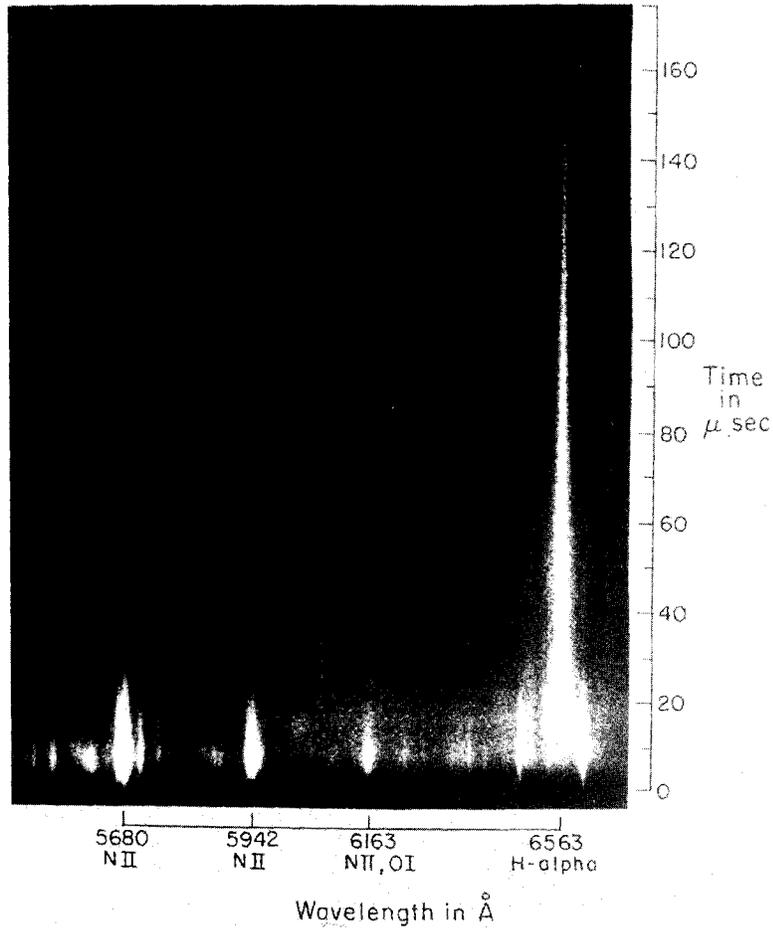


FIG. 9. Lightning return stroke spectrum versus time from a 10-m section of the lightning channel. Neutral atom spectra are designated I, singly ionized atom spectra II. H_{α} is from the hydrogen Balmer series. Data adapted from Orville (1968).

the channel pressure and the densities of all the particle constituents of the channel can be calculated if local thermodynamic equilibrium is assumed (Uman 1969b).

From lightning spectroscopic measurements and various laboratory

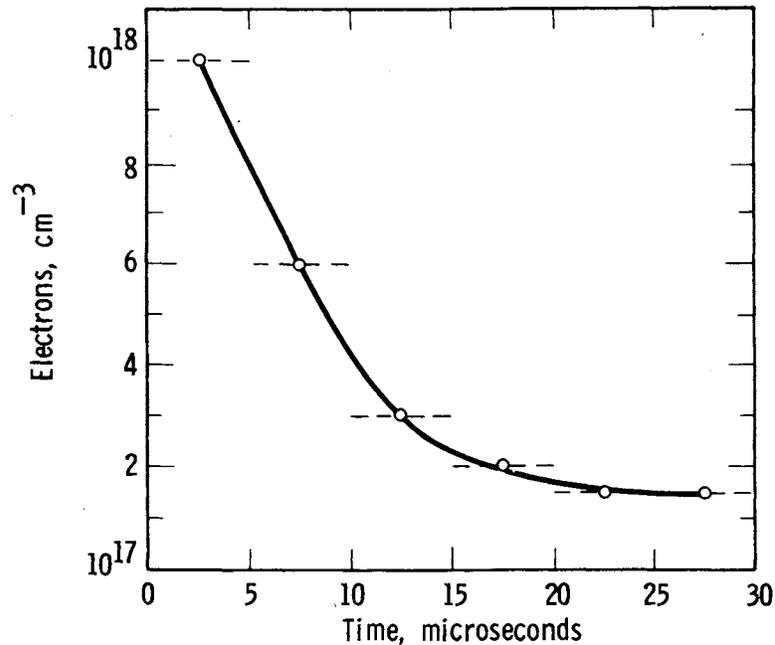


FIG. 10. Lightning return stroke electron density versus time. Dashed horizontal lines indicate the 5- μ s time resolution. Data adapted from Orville (1968).

measurements of simulated lightning the following picture has been assembled of the return stroke channel development. Consider a short section of the leader channel just as the return stroke arrives. The increase of current and electric field in the leader channel caused by the return stroke energy input transforms the leader into a high-temperature return stroke channel. The initial gas density in the return stroke channel is that characteristic of the leader just prior to the arrival of the return stroke wavefront, but the temperature is above 30,000°K. Since the leader channel was probably in pressure equilibrium (1 atmosphere) with the surrounding air before its temperature increased, the initial return stroke channel pressure must exceed the pressure of the surrounding air and the channel will expand. This expansion takes place with supersonic speed and produces

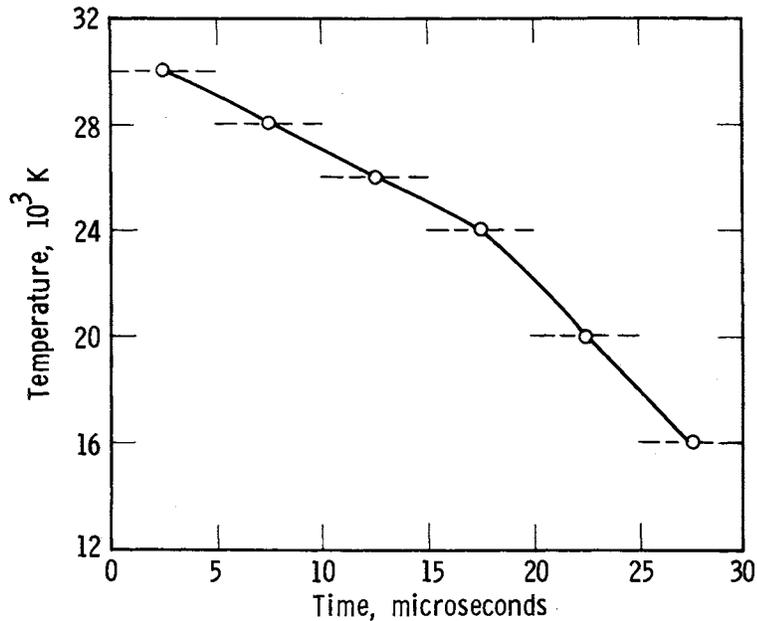


FIG. 11. Lightning return stroke temperature versus time. Dashed horizontal lines indicate the 5- μ s time resolution. Data adapted from Orville (1968).

a shock wave which eventually becomes the thunder we hear. The shock wave phase of the channel expansion lasts about 5 to 10 μ s. As the shock wave moves outward, the gas density in the current-carrying channel behind it decreases, and late in the shock-wave phase the temperature in the channel is near 30,000°K. After this phase of the channel expansion is completed, the high-temperature low-density channel approaches a state of approximate pressure equilibrium with the surrounding air. The spectroscopically derived data shown in Figures 10 and 11 indicate an average pressure in the first 5 μ sec of return stroke development of about 10 atmospheres. The channel pressure has decreased to about 1 atmosphere in about 20 μ sec.

One spectrum of the lightning stepped leader suitable for a tem-

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perature determination has been obtained by R. E. Orville. The spectrum of the newly formed leader steps are similar to those of the return stroke, indicating a narrow spark channel with a temperature between 20,000 and 35,000°K. A few step lengths above the newest leader step, the leader temperature was estimated to be about 15,000°K.

THUNDER

As we have seen in the previous section, the expanding return stroke channel acts as a piston creating an outward propagating shock wave. If the shock wave is generated by a given straight section of channel, it should be roughly a cylindrical shock until it is further away from the channel section than the length of that section. Beyond that point, the shock wave might be expected to make a transition to a spherical shock wave and eventually to a spherical sound wave. Since the lightning channel is very tortuous, it is reasonable to expect, to a first approximation, that thunder from distant lightning is the superposition of the many spherical sound waves produced at all points along the channel (Few et al. 1970).

Straightforward as the above might appear, the exact physical mechanism of thunder and even the properties of thunder are still in dispute today. As noted in the Introduction, Aristotle thought that thunder was due to the impact of "dry exhalation" on a cloud. Lucretius, two years later, wrote that thunder was due to clouds banging together. In 1637 Descartes, the mathematician after whom the cartesian coordinate system is named, suggested that thunder was an organ-pipe effect: that thunder was due to a resonance of the air between two clouds which occurred when a higher cloud descended upon a lower cloud.

These early theories erroneously associated thunder with clouds rather than with the lightning channel. Later speculation regarding the origin of thunder generally associated thunder with the lightning channel. For example, Benjamin Franklin wrote in 1749 that lightning and laboratory sparks were similar in that they both gave a "crack or noise in exploding." The correct meaning for Franklin's

“exploding” was not generally agreed upon until the 20th century. In the mid-19th century the accepted thunder theory seems to have been that lightning produced a vacuum along its path, with thunder resulting from the subsequent motion of air into the vacuum. Two other theories that achieved some respectability involved (1) the chemical explosion of gaseous materials created by the lightning, and (2) the creation of steam explosions along the heated lightning path. One of the first adequate descriptions of the origin of thunder was published by M. Hirn in 1888.

In 1914 W. Schmidt published the first record of the pressure variations due to thunder and began a controversy which is only now close to resolution. Schmidt used two different instruments to measure thunder pressure. The first, for frequencies in the 1 Hz range, was essentially a box with a single hole in one side in which was suspended a thin metal plate. The plate moved in response to the sound pressure impinging on it, the motion of the plate being recorded via levers attached to the plate. The second instrument, for frequencies from 25 to over 100 Hz, consisted of a megaphone at whose throat was a smokey turpentine flame which moved in response to the impinging pressure variations. The soot record was recorded on a motor driven strip of paper. Schmidt reported that the infrasonic pressure variations near 1 Hz were considerably stronger than those corresponding to the loudest audible sounds. The infrasonic thunder variations were reported to correspond in time with audible thunder claps. Almost 40 years elapsed from Schmidt's work until the next measurement of thunder pressure was reported. V. Arabadzhi then reported that indeed the maximum thunder energy was in the infrasonic frequencies, but that the strongest pressure variations were compressions rather than the rarefactions previously reported by Schmidt. It should be noted that the instruments used by Schmidt and Arabadzhi were similar narrow band instruments which could have well been set into resonant oscillations by the thunder. In the 1960's Bhartendu also reported that most thunder energy is infrasonic, but his experimental technique was strongly criticized by McCrory and Holmes (1968).

In the late 60's Few, Dessler, Latham, and Brook in studies carried

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out using modern microphones reported dominant thunder frequencies in the 50 to 200 Hz region with little low frequency energy. Frequencies in this range are expected from the theory of explosions (the lightning channel expansion is essentially an explosion) on the basis of reasonable values for the energy input to the lightning channel (Few 1969). Unfortunately, part of the reported data was in error due to a mistake in the data analysis [M. Brook 1969, private communication]. The most recent chapter in the thunder-frequency debate and perhaps the beginning of the resolution of the dispute between the high and low frequency advocates, has been the report by Holmes et al. (1971) that thunder exhibits *both* low (less than 10 Hz) and high (50 Hz and above) frequency peaks. They attribute the high frequency to the channel expansion mechanism and the low frequency to electrostatic relaxation processes occurring inside the cloud during a lightning flash.

One of the more interesting recent uses of thunder to study lightning has been the lightning channel reconstruction from thunder measurements made by an array of microphones (Few 1970). This audio triangulation technique allows the determination of lightning channel structure inside clouds where photographing the channels is usually impossible.

DISCUSSION

While much is known about lightning, more remains to be discovered. Probably the most serious deficiency in our understanding of lightning is the lack of good quantitative theories to describe leader and return stroke formation and propagation. Also poorly understood is the interaction of lightning with the thundercloud that produces it. In order to formulate useful models of lightning behavior, additional and more detailed experimental data are needed. For example, the phenomenon of leader stepping should be photographed (perhaps with an image converter or intensifier camera) on a sub-microsecond time scale. As an additional example of experimental work that could provide valuable information, studies are needed to expand the relatively small amount of data available on intracloud, intercloud, and cloud-to-air discharges.

THE PHYSICAL PARAMETERS OF LIGHTNING

In this paper little mention has been made of any of the practical benefits which have accrued from a detailed understanding of lightning behavior. Fundamental lightning data has been put to practical use in a variety of ways ranging from the design of sensitive communication systems which operate in the presence of lightning's electric and magnetic fields to the design of adequate protection from the direct effects of lightning for the electrical and mechanical components of NASA's upcoming Space Shuttle. Further understanding of certain aspects of lightning should yield additional practical benefits. A high level of understanding of lightning will make possible its control by man. One might expect this goal to be reached in a few tens of years.

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