

RETURN TO E.M. DEWAN

# ELECTRICAL BEHAVIOR OF AN AIRPLANE IN A THUNDERSTORM

## TECHNICAL REPORT



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by

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## ABSTRACT

By processes as yet poorly understood, extensive regions of both positive and negative electric charge form in large convective clouds. These clouds are the primary source of the lightning discharges that sometimes strike airplanes.

Airplanes in flight can develop electrical charges on their surface as the result of a variety of processes but the maximum amount of charge that they can carry is limited by point discharge and is negligibly small compared to the charge transferred by a lightning discharge. Although the amounts of net or induced charge on the airplane are small compared to the amount of charge in the thundercloud, these charges can locally cause an appreciable intensification of the electric field of a thunderstorm. While some lightning discharges to airplanes may be attributable to chance alone, there are reasons to believe that the electric charges on the airplane may either attract or initiate lightning discharges.

It does not appear to be feasible to produce a significant reduction in the probability of an airplane receiving a lightning discharge by any technique for controlling the charge on the airplane. The most promising solution to the hazards posed by lightning is to design airplanes so that they are capable of receiving discharges without damage.

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## INTRODUCTION

### OBJECTIVES

Experience has shown that when an airplane is flown in or near a thunderstorm it will be "struck" occasionally by lightning. Usually, the lightning does little or no damage and rarely poses a serious hazard. It is desirable nevertheless that all possible methods be investigated that will further reduce even this slight hazard. Such efforts are the concern of the government aviation agencies, the aircraft designers and manufacturers, equipment manufacturers, the airlines and those who fly and maintain the airplanes.

A considerable body of knowledge is presently available on the physics of 'static' electricity, the electrical structure of thunderstorms, and the nature of the lightning discharge, and it appears desirable to bring together pertinent information bearing on the problems of protecting an airplane from lightning. It should be noted that the scope of this effort is limited and that it has not been possible to deal in depth with the many problems such as the mechanisms of thunderstorm electrification, the physics of the lightning discharge, and the effect of lightning on the airplane. Those readers wishing to pursue the subject more thoroughly are referred to the bibliography at the end of this report.

The author hopes that this report may serve a secondary purpose in focusing attention on the various unsolved problems of the relationships between airplanes and lightning and help indicate desirable research approaches in this area.

There are so many wide areas of ignorance in the field of thunderstorm electrification that there is often a wide divergence of opinion among workers in this field. To insure that this discussion represents points of view about which there is some degree of consensus, the author was assisted in a preliminary screening of the subject matter by a panel consisting of Dr. Gilbert D. Kinzer of the U. S. Weather Bureau (Chairman), Dr. Jacob E. Dinger of the Naval Research Laboratory, and Dr. Donald R. Fitzgerald of the Air Force Cambridge Research Laboratory.

### LIGHTNING-PRODUCING CONDITIONS

Ions and electrically charged particles are normally present in the atmosphere at all times as the result of ionizing radiation, contact electrification, etc. Usually there are very nearly equal amounts of positive and negative charge everywhere and the atmosphere as a whole is electrically nearly neutral.



Under some conditions, however, certain volumes of the atmosphere may contain a high concentration of either positive or negative charge. Sometimes the net electric charges in these regions of the atmosphere may become large enough to build up disruptive forces sufficient to produce the long electrical sparks called lightning.

The most common producers of lightning are the clouds of thunderstorms or thundershowers, but it should be noted that lightning may occur in snow, dust or sand storms. Another vigorous source of lightning is the dense cloud over an erupting volcano. Some lightning is man-made, for sparks have been observed to form in the clear air around an exploding nuclear device. Lightning has been reported in the clear air at some distance from any storms McCaughan 1926, Gisborne 1928, Myers 1931, Gifford 1950, Baskin 1952, and such occurrences are responsible for the phrase "bolt from the blue."

## GENERAL FEATURES OF THUNDERSTORM ELECTRIFICATION

### DESCRIPTION OF THUNDERSTORM

All observations indicate that vigorous atmospheric electrification often occurs when tall clouds form with strong updrafts and downdrafts. Stimmel et al. (1946) have stated, "Extensive experience, flying in all types of weather, has shown that not only thunderstorms but all convective activities in the air are capable of causing charge separations that produce atmospheric electric fields."

The most common producer of lightning is the convective cloud system that forms when the atmosphere is unstable with cold, dense air aloft and buoyant, warm, moist air at lower levels. Such a condition arises when cold polar air masses overrun a warmer air mass, when cold air moves over a large lake or ocean having a higher temperature, or when land surfaces warmed by the sun communicate their heat to the air in the lower atmosphere. Under these conditions the atmosphere becomes unstable; the warm air at low levels rises in strong updrafts to form clouds, and the cold denser air aloft descends.

As is illustrated in Fig. 1, the size of these convective clouds which produce lightning is quite variable and ranges from the small warm clouds in the semi tropics which are only 4 km high to the giant electrical storm (Vonnegut and Moore, 1959), which towers to 20 km or more.

The typical thunderstorm has an altitude ranging between 8 and 12 km. Fig. 2 shows the general appearance of one of these with such features as the anvil cloud of ice crystals, the convective turret, the cloud base and the precipitation.

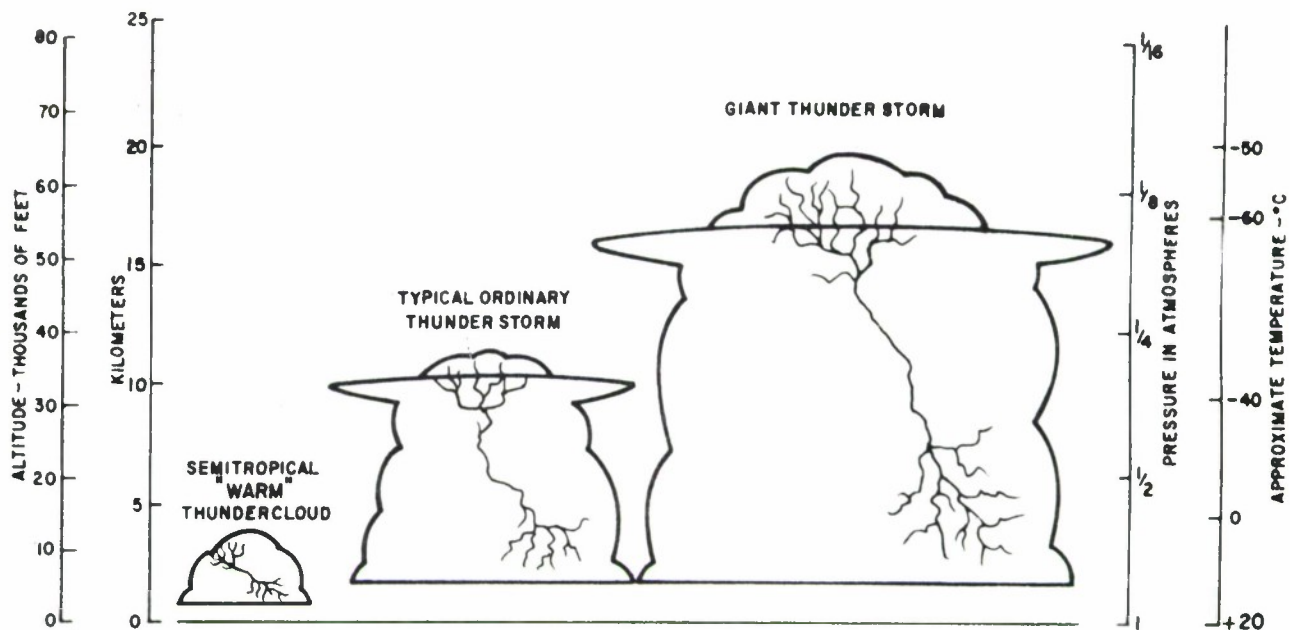


FIGURE 1 - Comparison of Various Sizes of Convective Clouds That Produce Lightning Discharges

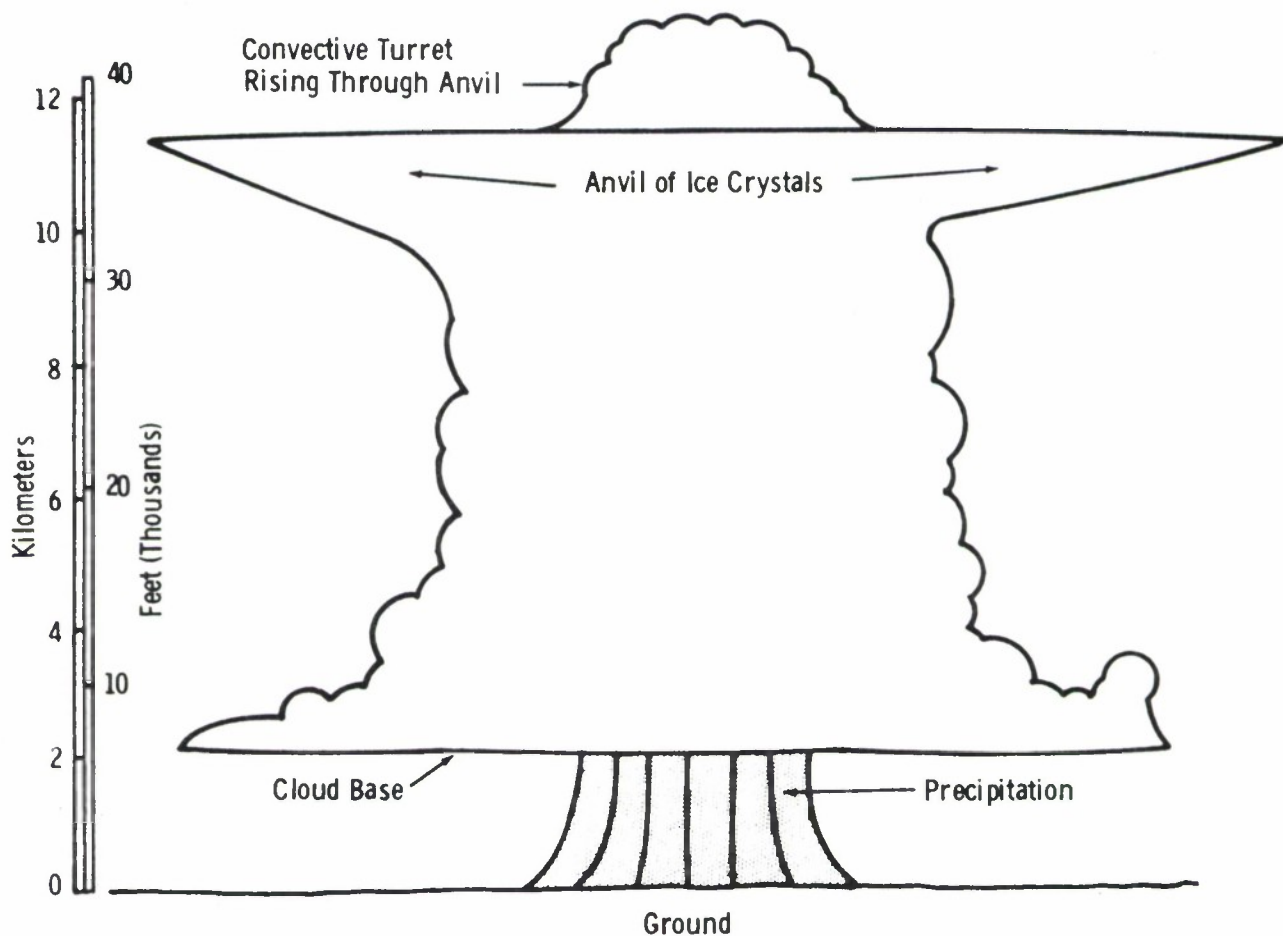


FIGURE 2 - General Features of a Typical Thundercloud

The electrical behavior of the thunderstorm is probably influenced by the motions of the air inside and outside of the cloud. Although our knowledge of the details of the circulation is still fragmentary, there is evidence for the general features illustrated in Fig. 3. Recent observations of the circulation with an instrumented high performance airplane show that the speed of the vertical air motions can be as high as  $63 \text{ m sec}^{-1}$  (Steiner and Rhyne, 1962).

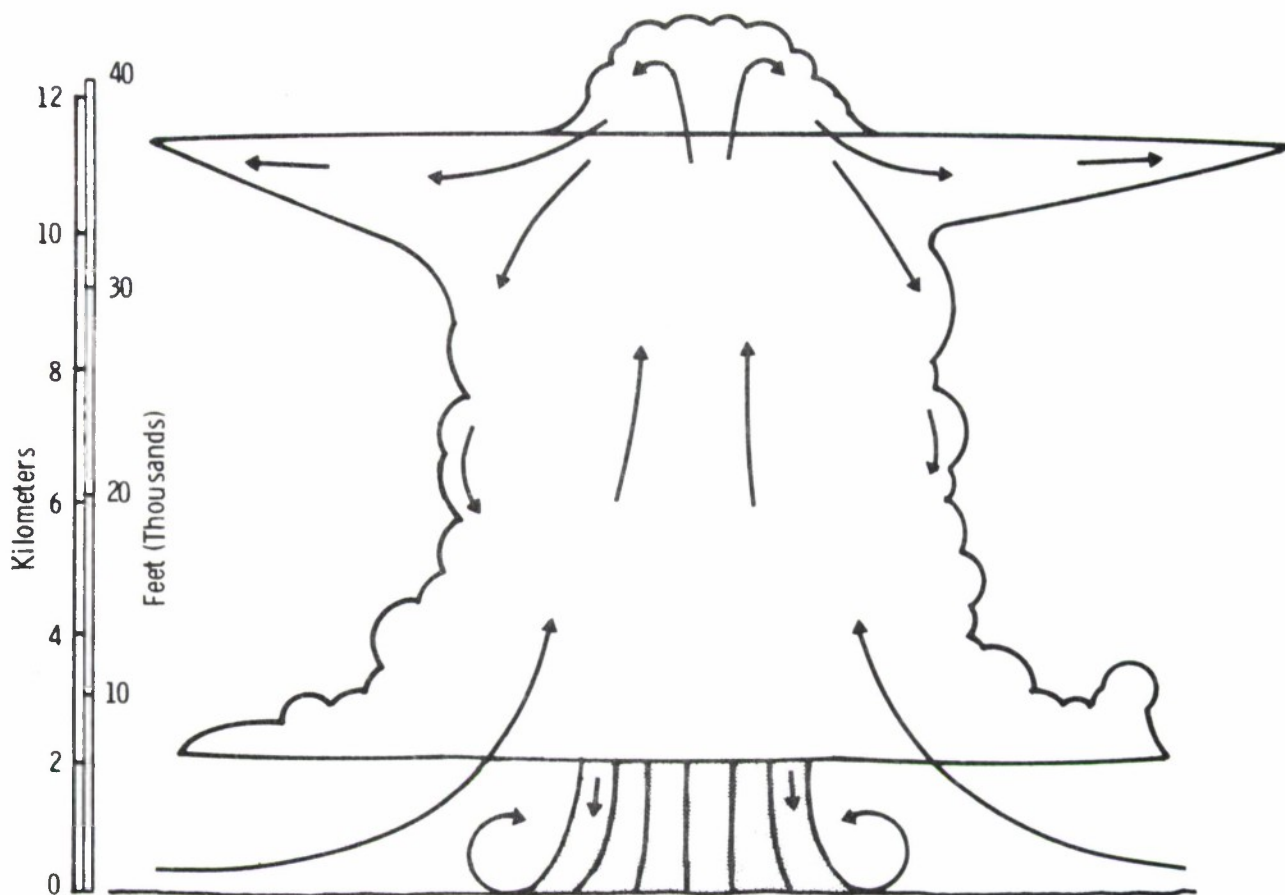


FIGURE 3 - Some of the Motions of the Air That Are Observed in a Thundercloud

Roughly speaking, the likelihood and frequency of lightning occurrence increases with the size and height of the storm, and the most active storms electrically are the very high ones that penetrate into the stratosphere. This is illustrated by the data of Shackford (1960) in Fig. 4 which show that the frequency of lightning increases with the height of the storm.

Although, in the semi tropics, thunderstorms have been reported that are nowhere below freezing temperatures (Pietrowski, 1960 and Moore et al., 1960), seldom if ever in temperate zones is lightning observed unless the cloud top is well above the  $0^{\circ}\text{C}$  level. This may indicate that the electrification process involves the presence of ice (Shackford, 1960), or that it depends critically on the size of the cloud (Vonnegut, 1963).





## LOCATION OF LIGHTNING

It is difficult to make useful generalizations concerning when and where lightning will occur in an electrified cloud. Sometimes the first lightning may occur in as little as twenty minutes after a cloud has formed, and sometimes an hour or more may elapse. Most of the lightning in the average thunderstorm take place within or between clouds, and only about ten percent occurs as discharges between clouds and the earth. Some lightning extends from the cloud to the clear air around or beneath the cloud. Occasionally lightning has been observed that goes vertically upward into the clear air above the cloud. (Wilson, 1920, 1946; Ashmore, 1950; Wright, 1950). In Fig. 5 we illustrate the locations in the thundercloud in which lightning is observed.

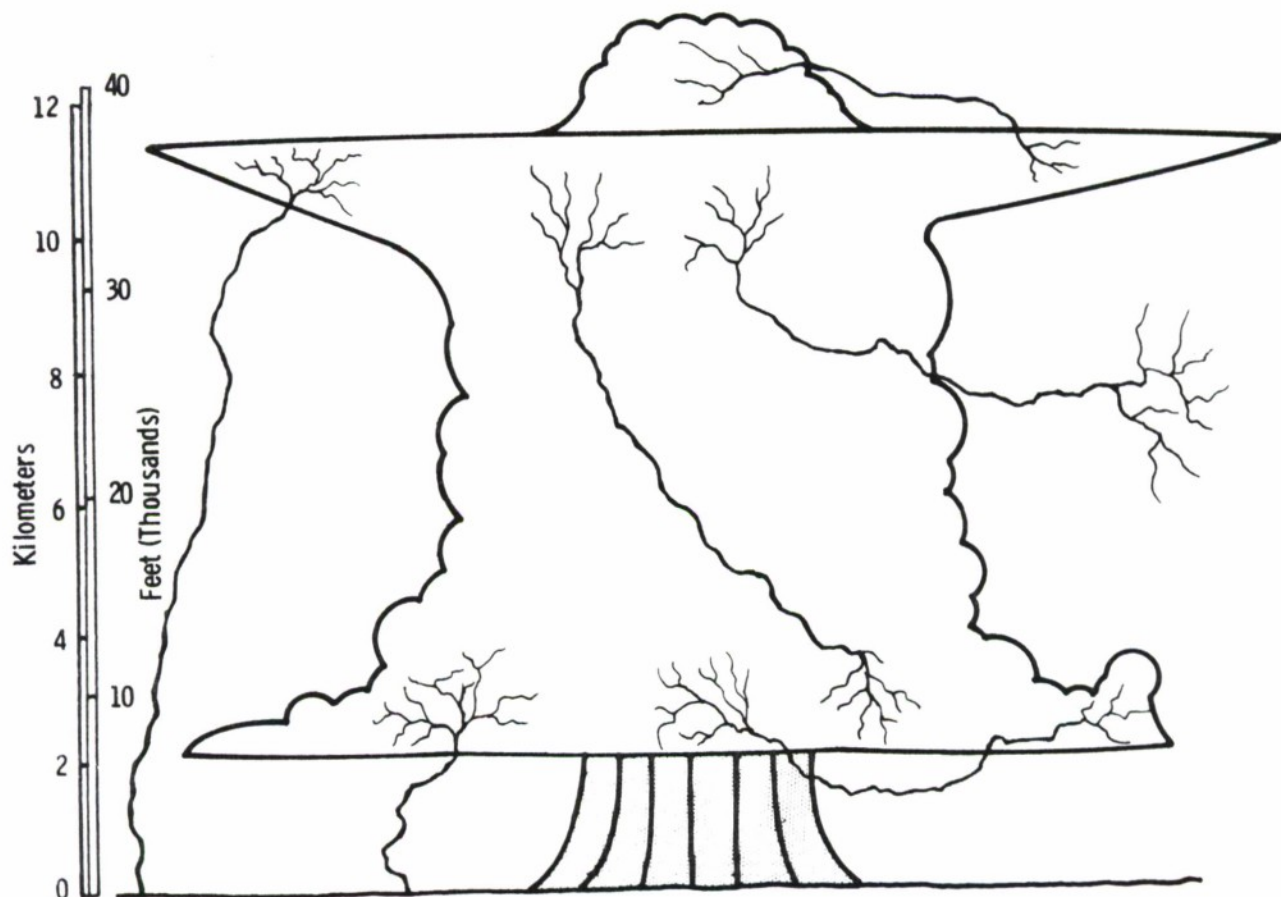


FIGURE 5 - Locations in the Thundercloud in which Lightning is Observed

Sometimes the lightning appears to be associated with regions of the storm giving precipitation, while at other times the lightning may occur in regions of the cloud or clear air where, to judge from radar evidence, little or no precipitation exists (Atlas, 1963; Moore et al., 1964; Mason, 1964).

Most of the lightning in a storm takes place during the period when the cloud is vigorously growing and active, but, occasionally, lightning strokes will occur when most of the convection and precipitation has ceased and a rather quiescent anvil is about all that remains of the storm.

#### ELECTRICALLY CHARGED REGIONS IN THE STORM

As the result of various investigations it is clear that the positive and negative charges in the thunderstorm reside on a variety of particles. Measurements outside of the cloud show that significant quantities of both positive and negative charge are to be found in the form of ionized air molecules and charged particles ranging in size from condensation nuclei and dust particles up to rain, snow, sleet and hail. Inside the cloud, in addition to all of these electrified particles, charged cloud droplets and ice crystals are also present.

While most students of thunderstorm electricity would agree that all of the above mentioned kinds of electrified particles are present in the thunderstorm, there is a wide divergence of opinion concerning the amounts of charge that each carries and its importance in the electrical processes taking place. This lack of agreement arises from the lack of good experimental data within a storm; it is extremely difficult to locate and to identify charge carriers and to measure their individual charges.

Although we remain largely ignorant of the nature of the charge carriers in the storm, we have a rough picture of the distribution of electrical charge. Observations continue to show, as Franklin was the first to observe, that the upper part of most storms carries a preponderance of positive charge while the lower part carries a preponderance of negative charge. Observations from the ground and from airplanes suggest that usually the electrically charged regions are of the order of a kilometer or two in diameter. From their measurements made beneath thunderstorms in New Mexico, Workman and Reynolds (1953) deduce that "the positive center has the appearance of occupying a diffuse area in the cloud as if it were blown upward by convective currents."

While the picture of the thunderstorm as an electrical dipole may sometimes be useful as a rough approximation, it must be recognized, as Gunn (1955) has pointed out, that this is a "poor fiction." The actual structure is much more complicated and variable, as one might well expect when it is considered that the lightning is moving large charges about in the storm (Moore et al., 1964) and that vigorous updrafts and downdrafts will often carry charged particles in complicated patterns. The investigations of Reynolds and Neill (1955) concerning the location of the charged regions involved in lightning strokes show that sometimes the dipole is tilted greatly and that occasionally the negative charge is at a higher altitude than the



positive. The investigations carried out by Malan and Schonland (1951) show that the multiple strokes of a cloud-to-ground lightning discharge go successively higher into the cloud and indicate that the negatively charged region can be in the form of a vertical column.

There is evidence to suggest that in addition to the primary positive charge in the upper part of the cloud and the primary negative charge in the lower part of the cloud there are other important regions of charge in the storm. The observations over the tops of thunderstorms from an airplane reported by Gish and Wait (1950) show that often after a lightning stroke the electric force reverses abruptly to a large value in the fair weather direction, thus indicating the presence of negative charge in the top of the cloud. In recently reported observations of the electric force over thunderstorms from a U2 airplane, Fitzgerald (1964) has shown that sometimes the anvil portion of the cloud carries a negative electric charge.

At the lower altitudes in the storm Gunn (1948) has observed often when his instrumented airplane flew from the clear air into the thundercloud that there was a sudden increase in the electric force, indicating that the exterior portion of the cloud may be covered with a region of charge having the opposite polarity of that within it.

Though the existence of such a layer of charge on the cloud surface appears to be physically plausible, it is worth noting that questions recently have been raised whether it actually exists. Fitzgerald (1964) has reported that he failed to observe such increases as his instrumented airplane entered the cloud, and he suggests that the increased electric force reported by previous observers may have been the result of autogenous charges that formed on the airplane when it entered the cloud rather than charges in the cloud itself.

Various investigators (Simpson and Robinson, 1940; Malan, 1962) have made observations from which they conclude that in addition to the positive charge in the upper part of the cloud there is sometimes also another region of positive charge in the lower part of the cloud.

Schonland (1928) and other investigators have shown that under the influence of the strong electric force produced by thunderstorms, vegetation and objects on the earth's surface emit large quantities of predominantly positive charge. (This process, known variously as point discharge, corona or St. Elmo's fire, will be discussed later.) We may therefore expect that as the result of this process there may be large areas of positive charge beneath the thundercloud, and Malan (1952) has suggested that charge formed in this way may be carried by convection up to the cloud base to form the lower positive charge discussed earlier.

If we indicate the various charged regions that we have discussed in the outline of a thunderstorm, we can obtain the composite picture of charge distribution shown in Fig. 6. It should be emphasized that this picture of charge distribution is highly tentative and is based on inadequate data. Better measurements will necessitate considerable revision of this preliminary picture.

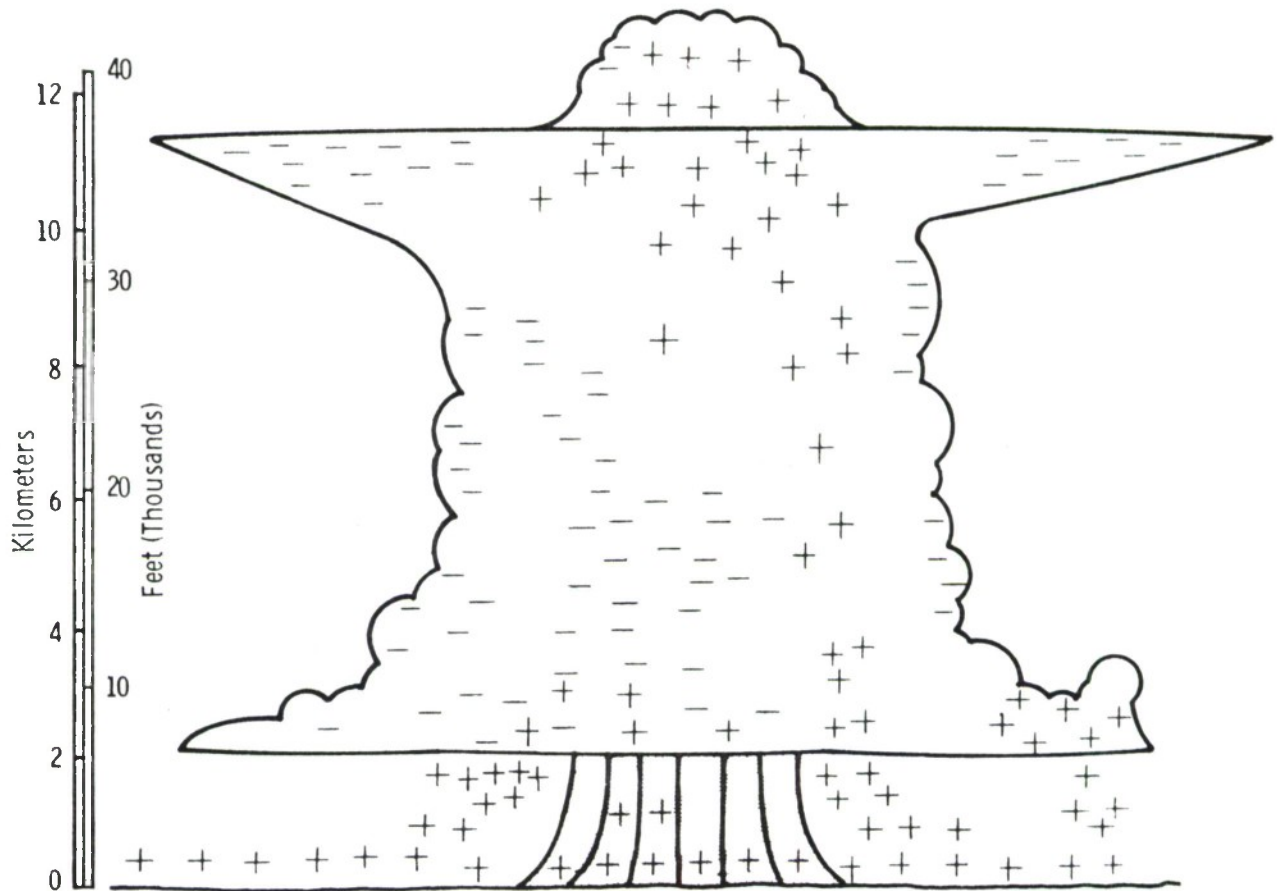


FIGURE 6 - Composite Picture Illustrating Roughly Where Various Investigators Have Observed Regions of Electric Charge in Thunderstorms

Estimates can be made of the amounts of charge in a thunderstorm on the basis of measurements of the electric force and the amounts of charge carried in lightning strokes. As might be expected, these estimates show great variations, ranging from values as low as a coulomb (Reynolds, 1955) to values as high as 1000 coulombs or more (Wormell, 1953). Visual observations such as those of Brook and Vonnegut (1960) and radar observations such as those of Ligda (1956) show that under some conditions horizontal chains of lightning sparks of 100 km or more in length can form. It appears probable that such strokes may transport rather large quantities of charge that are derived from a number of electrified regions in the storm.

#### THE ELECTRIC FIELD

A fundamental property of electric charge is the force that it exerts on other charges. An electric charge exercises a repelling force on charge of the same sign as itself and attracts charge of the opposite sign. A region

of forces called an electric field surrounds an electric charge.\* The magnitude of the local force (or, in the parlance of electricity and magnetism, the electric field strength or intensity) is usually expressed in volts per centimeter -- a measure, it will be noted, that has the units of work per unit charge per distance that a charge is moved.

One of the simplest electric fields is that around a spherical charge. Fig. 7 shows a representation of a positive charge by itself in space and a negative charge by itself in space. When more than one charge is present in a given space the electric field is the sum of the separate fields of the individual charges. A dipole in space would have the representation shown in Fig. 8.

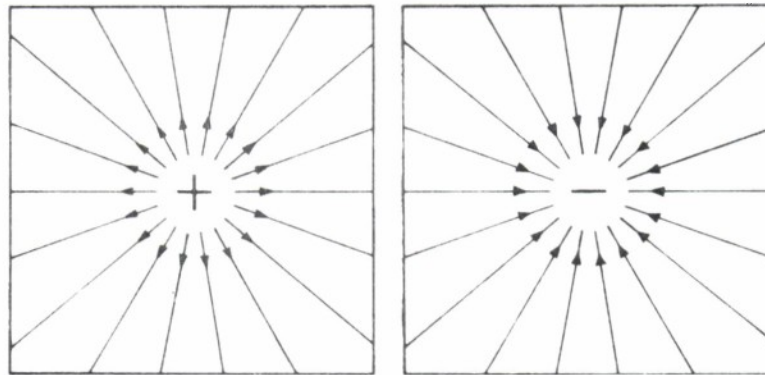


FIGURE 7 - Representations of Electric Fields of a Positive Charge and a Negative Charge

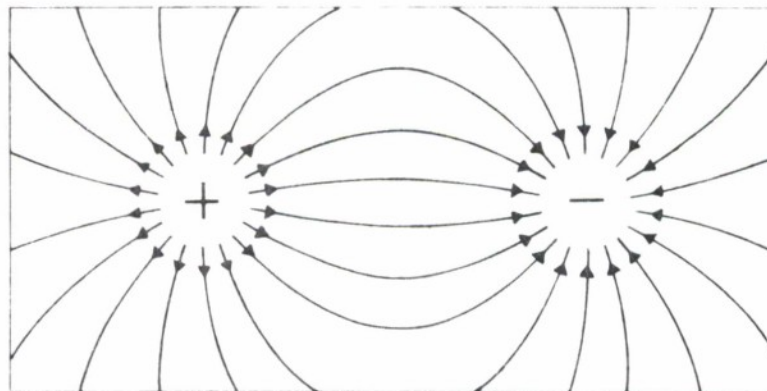


FIGURE 8 - The Electric Field Caused by a Dipole

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\* The electric field strength at any point in space is defined as the magnitude and direction of the electric force experienced by a unit of positive electric charge placed at this point. Since force has a direction as well as a magnitude, the electric field strength also has a direction as well as a magnitude. The field strength of an electric charge concentrated at a point varies directly as the amount of charge and inversely as the square of the distance away from it. We can indicate the direction and magnitude of the field by a number of imaginary "lines of force" whose directions indicate the directions of the force and density of which indicates the magnitude of the force.



As we have already discussed, the thunderstorm can be crudely approximated as a dipole, but because of the presence of the ground and the electrically conductive clear atmosphere above the cloud, its field is more complicated than that of a simple dipole in space. The earth is a fairly good electrical conductor, and under the influence of the electric charges in the cloud, an induced electric charge is attracted to the surface of the earth near the storm. The conductivity of the clear air above the storm increases rapidly with altitude, and similar induced charges probably form in this region too. The idealized electric field about the storm is therefore probably something like that shown in Fig. 9.

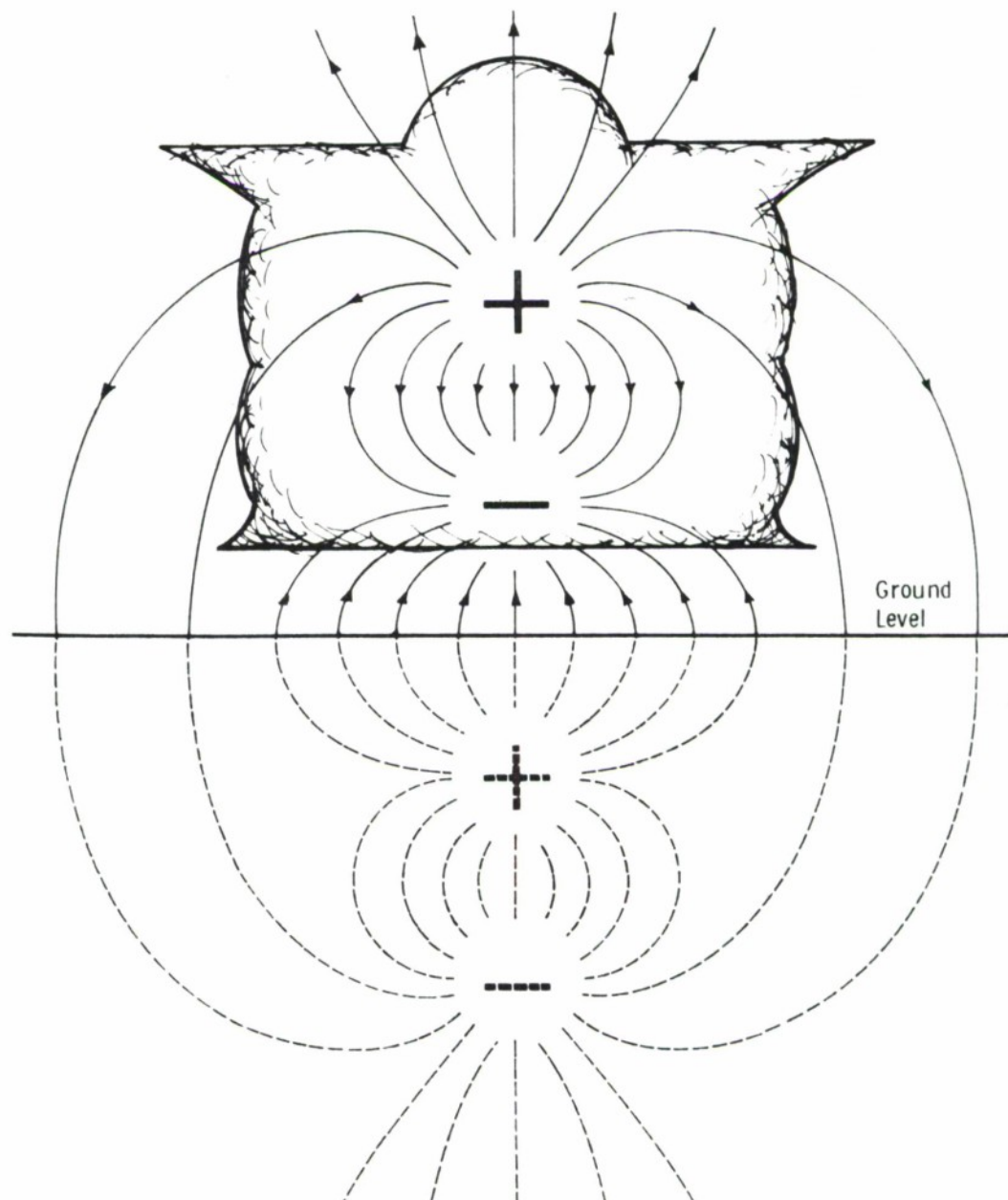


FIGURE 9 - Idealized Representation of the Electric Field of a Thunderstorm and Its Image (Indicated by Dashed Lines)

Although this picture of the electric field of a storm is oversimplified, it illustrates several important features of thunderstorm electricity:

- (a) The electric field increases as one approaches a charged cloud.
- (b) At the surface of the earth beneath the cloud the electric field is usually much smaller than it is in the cloud.
- (c) At the surface of the earth the electric field is always oriented perpendicular to the surface.
- (d) Beneath a charged cloud the direction of the electric field is usually positive; i.e., an upward force is exerted on a positive charge. The intensity of this field decreases with increasing distance from the cloud dipole, and finally it reverses to become a negative field.

It can be seen from the diagram that within or near the cloud the electric field may have any direction. This feature of cloud electrification adds to the difficulties of making measurements, because at any appreciable distance above the ground it is necessary to measure all three components of the field. The electric field associated with a thunderstorm is highly variable, and the magnitude and direction change not only with position but also with time.

The changes in the field with respect to time are of two kinds: the relatively slow ones associated with charging and conduction currents, and the very rapid changes caused by the lightning discharge. In the slow field changes the field may alter by a factor of two in either direction in seconds or minutes. When lightning occurs, the field may change its polarity or magnitude greatly in a few microseconds; such changes may take place many times per second.

When one remembers that some distance above the ground the field may have any direction, it is clear that with every change in the field magnitude there is undoubtedly a change in direction too, and the process is a most complicated and unpredictable one dependent on the charge distribution.

Measurements made of the electric field near the ground show that during a thunderstorm its magnitude often increases from the fine weather value of one or two  $\text{v cm}^{-1}$  to twenty, forty or even one hundred  $\text{v cm}^{-1}$ . This field may be either positive or negative, though it is more commonly positive (the anti fine weather direction).

Above the thunderstorm the electric field is far more complicated than the simple picture shown in Fig. 9. An actual record obtained by Fitzgerald (1964) during a flight in a U2 over a thunderstorm is shown in Fig. 10.

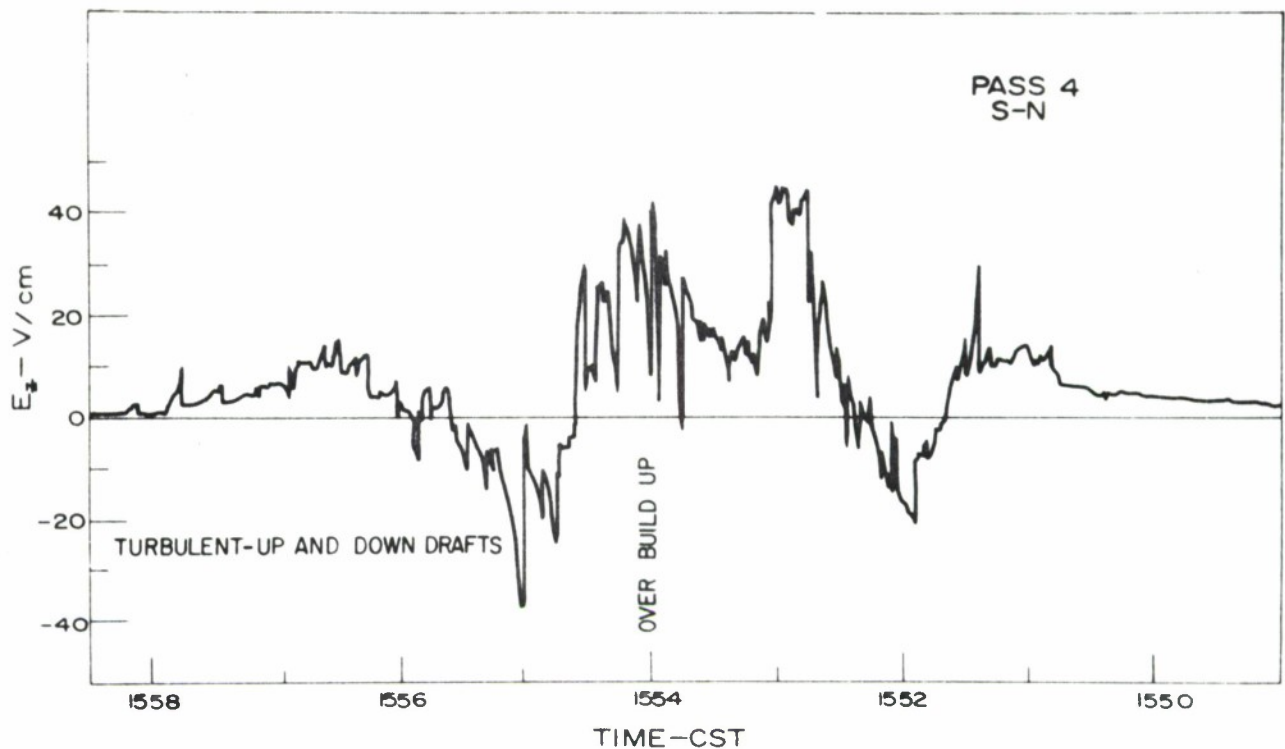


FIGURE 10 - Record Showing the Structure of the Electric Field as Observed from a U2 Aircraft Flown Over a Thundercloud (after Fitzgerald 1964)

As we have already indicated, the electric field on the ground is less intense than it is up in the cloud because of relatively greater distance from the charged regions that are causing the field. The field strength at the ground is further reduced by point discharge or corona (which we will discuss later). At the surface of the ocean and other bodies of water where there are no structures to provide point discharges, there is evidence that the fields may become more intense than over the ground, perhaps by as much as a factor of ten.

Measurements made by Gunn (1948) from an airplane inside of a thundercloud (see Fig. 11) indicate that just before a lightning discharge the electric field strength may reach values of several thousand  $\text{v cm}^{-1}$ . Estimates such as that made by Reynolds (1954) indicate that intense fields as large as ten thousand  $\text{v cm}^{-1}$  may occur. These values of the intensity of the electric field are for regions having dimensions of at least hundreds of meters and are for periods of time of seconds or more. It should be recognized that very much more intense fields can prevail over small distances and for very small periods of time. Investigations such as those of Doyle et al. (1964) have shown that over surfaces having radii of curvature of the order of less than 1 mm the intensity of the electric field can reach values in excess of  $10^5 \text{ v cm}^{-1}$ . During the very brief periods of the lightning discharge it is probable that in the region of the discharge the electric field intensity may for a few microseconds attain very high values.

The electric field produced by the thunderstorm can be considerably modified by the presence of an electrical conductor.\* When a conductor is placed in an electric field, the charge carriers, which may be electrons or ions, move under this influence of the field until by this change of position they assume a new distribution in which they completely cancel out any field within the conductor. Although this movement of charge within the conductor eliminates the field within the conductor, the accumulation of charge on the surface of the conductor increases the electric field intensity in some regions around the conductor.

### THUNDERSTORM OF AUGUST 5, 1944

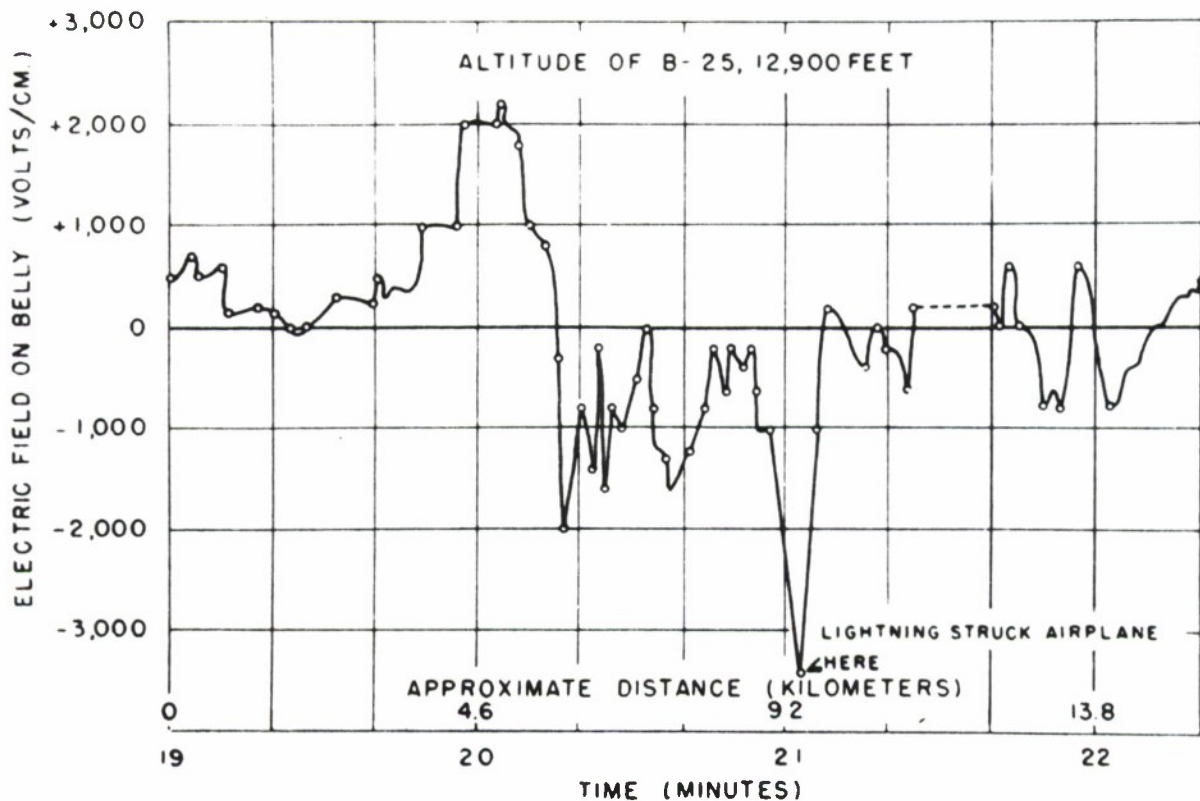


FIGURE 11 - Recording of the Electric Field Intensity on the Belly of a B25 Airplane When It Penetrated an Active Thundercloud and Was Struck by Lightning (Gunn 1948)

It can be shown that the accumulations of charge on the surface of a conducting sphere such as a cloud or raindrop causes a three-fold increase in the electric field at diametrically opposite positions in line with the superimposed field. The increase in the electric field intensity by this induction process over the surface of a sphere is shown in Fig. 12.

\* An electrical conductor is by definition a substance containing electrically charged particles that are free to move under the influence of an electric field.



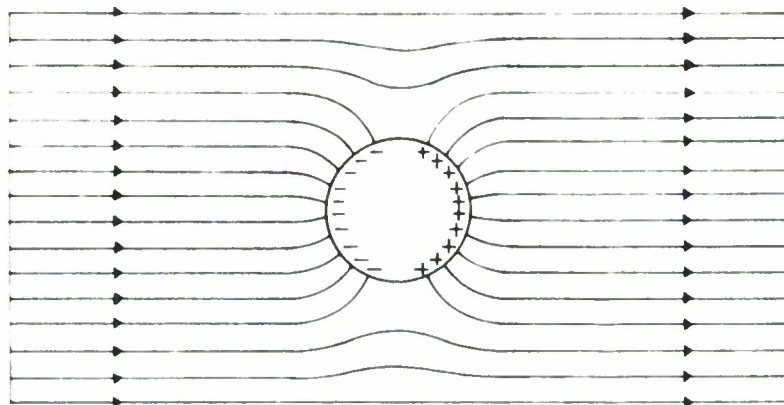


FIGURE 12 - Intensification of the Electric Field  
Produced by Induced Charges on the Surface of  
a Conducting Sphere

When the electrically conducting object is in the form of structures such as trees, towers and wires, the intensity of the electric field may be increased locally by many orders of magnitude. This process is illustrated in Fig. 13. The concentration of lines of force by objects on the earth's surface under a thunderstorm is one of the very important electrical processes taking place.

#### ELECTRIC CURRENTS

The electric charges in a thunderstorm are far from being static. They are, on the contrary, in a perpetual state of flux. Investigations of thunderstorms show that a variety of electric currents are flowing. Lightning discharges having instantaneous currents of hundreds of kiloamperes may carry charge at an average rate of an ampere within the cloud. In the conductive clear air above the storm Gish and Wait (1950) have deduced from their observation of the electric field and atmospheric conductivity that conduction currents of the order of an ampere flow to the upper positive part of the cloud. Beneath the cloud Schonland (1928) and Wormell (1930) have shown that the falling precipitation brings down positive charge at about one tenth of an ampere, and this is balanced by an approximately equal and opposite flux of negative charge brought down by lightning. By far the largest current flowing from the cloud to the earth results from point discharge. When the electric field intensity at the ground reaches about  $10 \text{ v cm}^{-1}$  the electric field at the tops of trees and other elevated structures becomes so large that dielectric breakdown of the air occurs and, depending on the field, either positive or negative ions are released into the atmosphere. In this process, called point discharge or corona when it is difficult to see and St. Elmo's fire when it is clearly visible, the ions that are released serve to reduce the electric field and thus limit the process, as is illustrated in Fig. 14. Measurements indicate that in a thunderstorm there is flux of about an ampere or more of positive charge from the earth to the cloud as the result of this mechanism (Schonland 1928).

Our knowledge of the currents flowing within the cloud is limited, but it is clear that the sum of the currents produced by falling charged precipitation and the transport of charged particles in updrafts and downdrafts must be of the order of an ampere or more to sustain the lightning and the currents flowing from the clear air above and beneath the cloud.

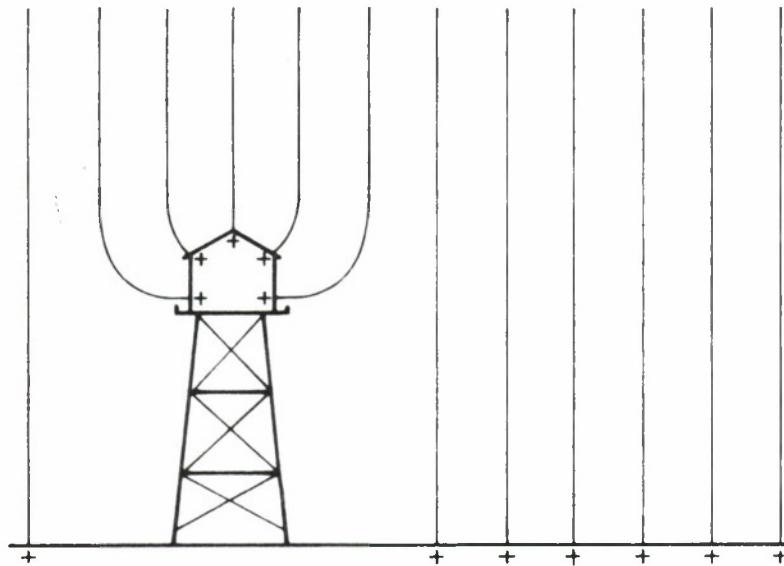


FIGURE 13 - Intensification of the Electric Field  
Caused by Electrically Grounded Conductive  
Structure on the Earth's Surface

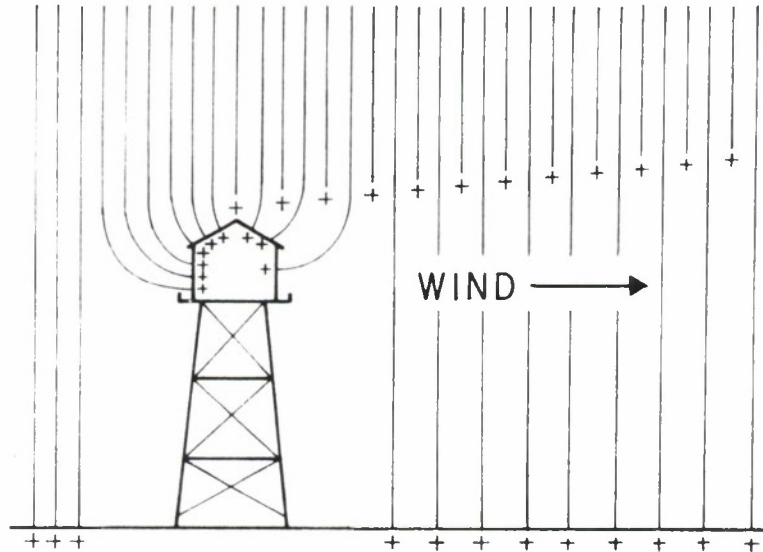


FIGURE 14 - When the Electric Field Rises Above  
a Certain Value, Point Discharge Occurs and  
Ions are Released into the Atmosphere and  
Carried Off by the Wind

In Fig. 15 we have indicated present ideas concerning the direction and magnitude of the electrical currents flowing in the thunderstorm.

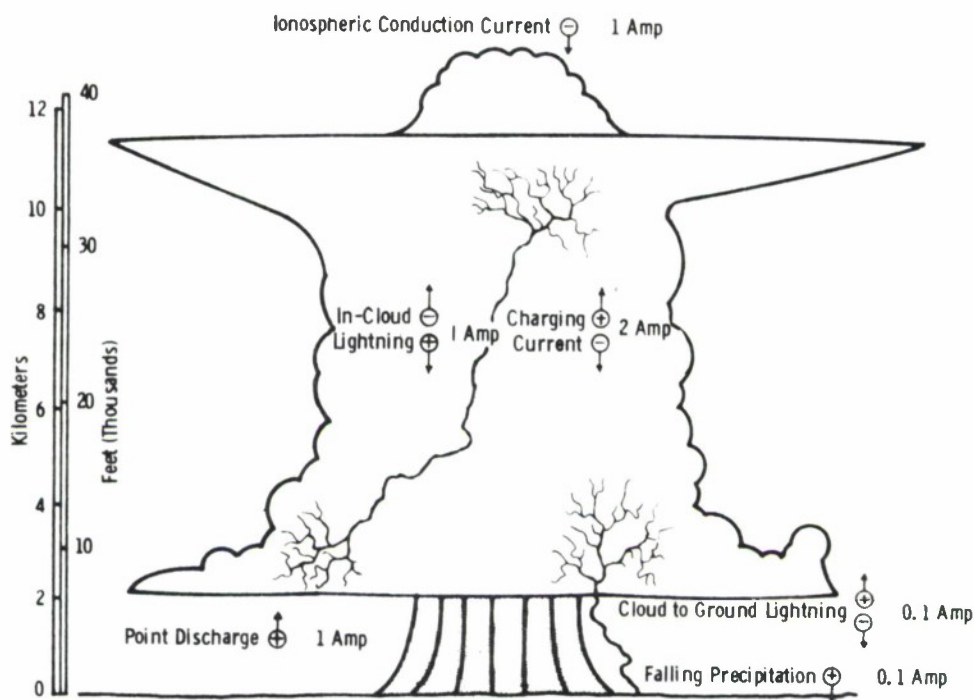


FIGURE 15 - Approximate Values of the Electrical Currents Believed to Flow in an Average Thunderstorm. (The charging current responsible for the cloud electrification, as Schonland indicates (1953), must not only provide the charges necessary for the lightning but also the charges necessary for the conduction and point discharge current. It therefore must probably be of the order of 2 amperes. The circled positive and negative charge symbols with arrows indicate the sign and direction of motion of the moving charged particles comprising the various currents in the storm.)

### POTENTIAL DIFFERENCES

In dealing with electrical problems such as the thunderstorm it is convenient to utilize the concept of potential difference between two points, which is defined as the work required to move a unit charge between the two points.\*

On the basis of the estimated charges and the measured electric fields in thunderstorms it can be computed that as the result of the charge in the cloud the potential there may be as much as  $\pm 10^8$  or  $10^9$  volts relative to the earth.

\*This electrical work is determined by integrating over the total distance the product of a differential distance times the force acting in the line of motion as the charge is moved from one point to another. The potential difference between two points is independent of the path taken between them.



It is worth noting at this point that electric charge and electric potential are two very different concepts that should not be confused.\* The potential is a value that depends first on the assumption of an arbitrary zero potential. (In atmospheric electricity the earth is usually assumed to be at zero potential.) Once this frame of reference is assumed, the potential of a point or an object is determined not only by the charge at the point or on the object but also by all the other electric charges that may be present. The object may very well have no charge at all and be at a high potential, or it may have a great deal of charge and be at zero potential. A charge-free airplane flying near a thunderstorm may very well be in a location where its potential is a hundred megavolts, and a sudden lightning flash may neutralize cloud charges in such a way that airplane potential will drop to a value near zero. Meanwhile, in spite of this large change in potential, the charge on the airplane may not change.

### NATURE OF LIGHTNING DISCHARGES

When large volumes of electric charge accumulate in the thundercloud and produce electric field intensities of the order of several thousand  $\text{v cm}^{-1}$ , a process called "dielectric breakdown" suddenly occurs. The atmosphere, which is normally a poor conductor of electricity, suddenly becomes locally highly conductive, emits light, and allows large electric currents to flow. This phenomenon is apparently caused by the sudden occurrence of an electrical avalanche in which, as the result of the action of the electric field, an electron or ion in the atmosphere acquires a sufficient velocity that when it collides with air molecules it liberates more electrons which in turn acquire sufficient velocities to repeat the process and form a conducting, ionized channel. The highly luminous spark discharges formed in this ionized channel are known as lightning. The physics of the formation of lightning is not well understood and it will not be discussed in this report.

The lightning discharge takes a number of different forms; Schonland has enumerated the following three main types:

(a) Streak or forked lightning or a flash to ground (foudre, Zickzackblitz, Linienblitz), popularly called a thunderbolt. This is a discharge that passes between clouds or between a cloud and the earth, adopting a tortuous course and sometimes forked from a main channel or trunk.

(b) Cloud discharges (eclairs dans le nuage), which take place within a thundercloud and are popularly called sheet lightning. These give a diffuse illumination, and no distinct channel is usually seen.

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\*Charge is a discrete quantity of electricity, either positive or negative. Potential difference is, according to our definition in a previous footnote, the amount of work required to move a unit positive test charge from one place to another in the field of force of nearby fixed charges. Since forces between charges vary inversely as the square of the distance of separation, the potential at an infinite distance from any group of charges is considered to be zero. It is more useful to assign arbitrarily a zero potential to the earth so that any grounded conductor will be at this zero potential. Any ungrounded object such as a flying airplane will have a potential depending upon its position and upon the electric forces exerted by electric charges everywhere, including the charge on the airplane if any.



(c) Air discharges (éclairs dans l'air, decharges atmospheriques): Sinuous discharges, often with a long horizontal section, that pass from a thundercloud into the air without striking the ground.\*

He notes also these subsidiary types:

(a1) Ribbon lightning (éclair en ruban): A flash to ground in which the channels of component successive strokes are separated by the wind to form a broad ribbon.

(a2) Bead or chain lightning (éclair en chapelet, Perlschnurblitz): A phenomenon which may follow forked lightning, the channel to ground breaking up into fragments some 50 meters in length, which become roughly globular and may persist for an appreciable time.

(a3) Ball lightning (éclair en boule, Kugelblitz): A luminous globe usually reported to appear soon after a discharge to ground. Its diameter has been reported to lie between 10 and 20 cm and occasionally to reach one meter. It moves slowly in the air or on the ground and usually disappears with a violent explosion.

(c1) Rocket lightning (éclair en fusée): An air discharge that gives the impression of fairly slow visible progression along its channel and branches.

The literature contains descriptions of still other types of lightning. Discharges have been described that come out of the top of the cloud and go vertically upward (Wright, 1950, Ashmore, 1950). A sketch of this phenomenon is shown in Fig. 16. According to the observer (Wood 1951), this discharge differed from the usual lightning flash in that it appeared as a "beam" of purple color similar to a low pressure discharge and lasted for as long as one second. Such lightning is sometimes given the name "Flachenblitz" (Ashmore, 1950).

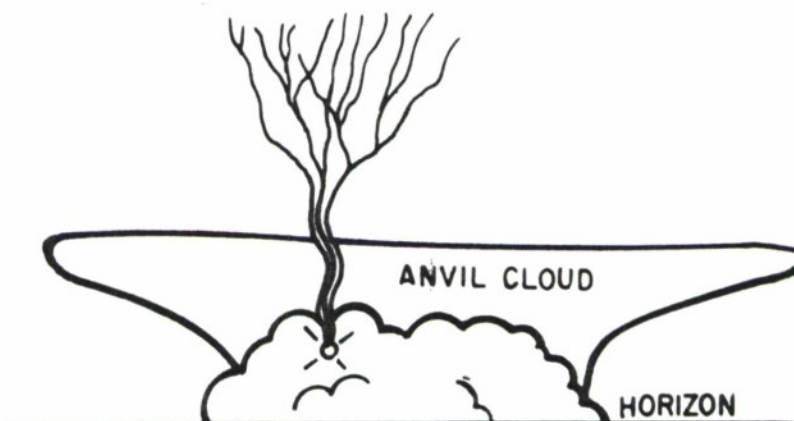


FIGURE 16 - Electric Discharge from Cloud Toward Upper Atmosphere (After Wood, 1951)

\*Sometimes air discharges apparently terminate in clear air; at other times the sinuous sparks extend from one cloud to another in long horizontal chains.

Observers of tornadoes describe a variety of lightning in or near the funnel that appears as a blue flame, flashes like a welder's arc, or a luminous cloud (Vonnegut and Moore, 1959).

Although some discussions are to be found in the technical literature concerning the possible nature of ball lightning and these other unusual electrical discharges (Dewan, 1964), our knowledge is presently fragmentary indeed. Some investigators even go so far as to question the existence of these phenomena. While, in the opinion of the author, there is no doubt concerning the existence of ball lightning and glow or arc type atmospheric electrical discharges, this discussion will be confined to ordinary lightning. This will be done not because these other kinds of lightning are unimportant or harmless but because we presently know so little about them. In doing this we may take some consolation in the fact that the chances of encountering these kinds of lightning are apparently quite small.

### LIGHTNING DISCHARGE PROCESSES

Lightning is usually initiated with the cloud, where the details of the process cannot be seen and observations are difficult. Our knowledge of what is happening is therefore fragmentary. A generally accepted possible explanation for the initiation of lightning is that it originates as the result of the electric field concentration at a raindrop or an ice crystal. The process can probably be initiated in a number of other ways, too -- for example, by cosmic radiation, meteorites, and by the field intensifications produced by airborne particulate matter such as seeds, birds, and insects. Quite often it will be noted that when several thunderclouds are active together, lightning discharges in one are often associated with lightning in the other. Very probably the sudden field change caused by lightning in one storm may serve to trigger lightning in another.

All of the evidence suggests that the exact time and place of the initiation of lightning is quite unpredictable, although it is sometimes possible to extrapolate from the past behavior of the storm and to guess approximately when and where the next spark will happen.

Photographs of lightning taken with a moving lens or moving film camera show that usually in the first part of the discharge a rather faint spark called a stepped leader descends from the cloud and in a discontinuous motion advances toward the earth in steps of about 20 meters. The average velocity of the stepped leader is about  $10^7$  cm sec<sup>-1</sup> or only a few thousandths of the speed of light.

The path taken by the initial stepped leader is the path of the lightning stroke, and its general direction is determined by the electric field. Some authors such as Malan (1963) have stated the opinion that the details of the tortuous course of the spark are determined by an irregular distribution of space charge in the atmosphere that attracts the leader first in one direction and then the other. While the effect of large space charges on the course of the spark is undeniable, it appears somewhat doubtful if sufficiently concentrated small charges exist to produce the frequent, small, sharp inflexions of the spark. Indeed, one finds in the laboratory that sparks pursue a similar course even when no space charge is present.



When the stepped leader approaches to within 10 meters or less from the ground or a grounded object, an electric discharge called a streamer is observed to begin at the ground or the object and to rise to meet the stepped leader. When the stepped leader has made this contact with the ground, a great current commences to flow from the channel, and an increase in the luminosity of the channel (the return stroke) proceeds toward the cloud with a velocity of about  $5 \times 10^9$  cm sec<sup>-1</sup>. Following the transfer of this charge in the return stroke, the luminosity of the channel ceases; in some cases this marks the end of the discharge. In most cases, however, the lightning discharge consists of several strokes; about twenty milliseconds after the first return stroke a new luminosity called a continuous or dart leader appears, descending down the channel from the cloud at a fairly constant velocity of about  $10^8$  to  $10^9$  cm sec<sup>-1</sup>. When the continuous leader reaches the ground, it is followed by another return stroke. While most lightning discharges consist of three or four strokes, discharges having over twenty have been reported (Malan 1963). In contrast to laboratory spark discharge of oscillatory circuits, the charge in lightning appears to move only in one direction; i.e. lightning currents seem to be unidirectional.

These charge movements or currents are subject to wide variation. During the return stroke the current is commonly of the order of 25 ka and can on occasion reach values in excess of 200 ka Newman (1964). Such high currents are usually of very brief duration, lasting only of the order of 50 microseconds and transferring only a few coulombs per stroke. In addition to the brief, very large currents associated with the return stroke there are smaller, prolonged currents of the order of a few hundred amperes that flow during the interval between strokes. As Williams and Brook (1963) point out, these long-duration, low-current discharges are a principal charge transfer mechanism. Fig. 17 is a schematic representation taken from their paper illustrating the events in a lightning flash in which continuing currents play a part.

While most lightning strokes are initiated within the cloud, several exceptions should be noted. It has been found that very tall structures such as the Empire State Building (McEachron, 1939; 1951) in New York City and the high masts used for television antennas sometimes initiate the formation of a stepped leader that proceeds upward to the cloud. The rapid insertion of a conductor of some size into a strong electric field can initiate a spark. Fig. 18 shows how a plume of water rising from the sea as the result of the firing of a depth charge triggered a lightning discharge. Presumably the intense electric field at the tip of the advancing plume initiated the formation of a stepped leader. Brook et al. (1961) have shown in laboratory experiments with a large Van de Graaff generator that it is possible to initiate a spark discharge by rapidly introducing a grounded wire. Newman (1965) has successfully triggered the formation of a lightning discharge by firing up a rocket carrying a wire from a ship beneath a thunderstorm cloud.

Most of the information in the foregoing discussion is based on investigations of lightning discharges from the cloud to ground. It is considerably more difficult to observe cloud-to-cloud flashes, so that much less is known about this variety. It appears that the flash begins with a stepped leader, as is the case with the cloud-to-ground discharge, but that in contrast to the cloud-to-ground discharge the channel remains luminous throughout the duration of the flash with intermittent bursts of higher intensity. While successive strokes

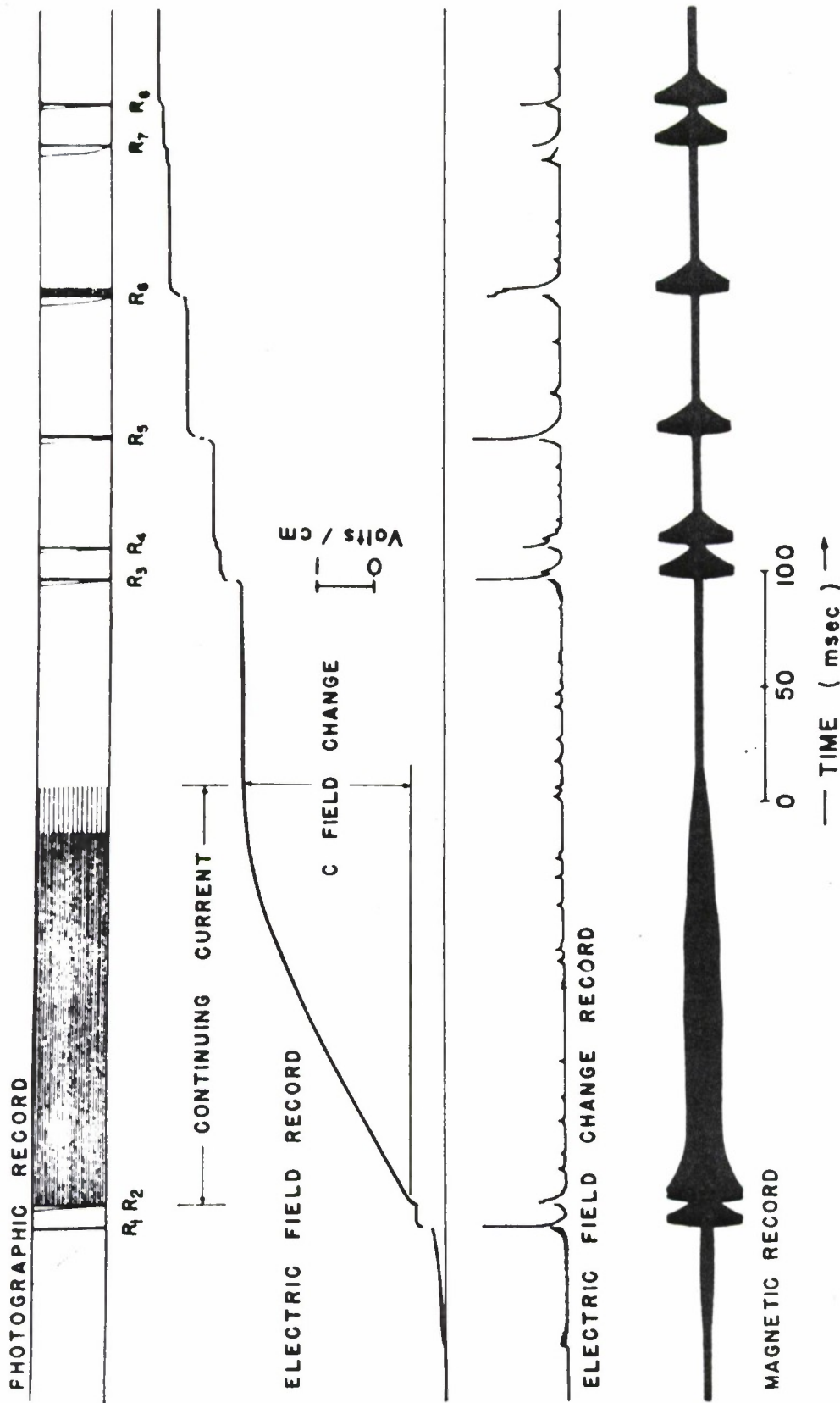


FIGURE 17 - Schematic Diagram after Williams and Brook (1963) Showing the Events in a Lightning Flash as Seen Simultaneously by Photographic, Electrostatic, and Magnetic Instruments. The events labeled  $R_1 R_2, \dots$ , are discrete return strokes, each preceded by a leader. The continuing current after return stroke  $R_2$  is typical of the long-continuing currents discussed in this paper. The slow decay in the amplitude of the magnetic signal after the return strokes is a result of the long time constant (20 ms) of the instrument. Note the magnitude of the continuing-current field change as compared with the return-stroke field change on the electric field record.





FIGURE 18 - Lightning Discharge Initiated by the  
Rising Plume of Water from an Underwater  
Explosion (after Young, 1962)

of the cloud-ground discharge take place through the same channel beneath the cloud, the evidence suggests that within the cloud the successive discharges tap regions of space charge in different parts of the cloud or even in different clouds. Brook and Vonnegut (1960) have described visual observations indicating that this may be the case.

In most cases the lightning discharges are associated with the active parts of the thunderstorm where the convection and precipitation are most intense. Sometimes, however, the lightning may take place at a considerable distance from radar precipitation echoes (Atlas, 1963), even in the clear air.

It appears that most flashes carry charge between charged regions of opposite polarity or between a charged region and the ground. The effect of the discharge is thus to bring two opposite charges closer together so that an electric dipole disappears. This may not be true of all lightning, for it is possible that some discharges may transport charge from a highly charged volume to a greater distance without involving charge neutralization. Discharges that are sometimes observed to terminate in the clear air around a cloud may be transferring charge from the interior of the cloud to an uncharged region around it.

## ELECTRICAL BEHAVIOR OF AIRPLANE IN A THUNDERSTORM

### INDUCED CHARGE ON AIRPLANE

If the fuselage of an airplane is an electrical conductor, as is normally the case, accumulations of induced electric charges will form on the airplane surface when the airplane is in an electric field. This separation of charge as the result of an external electric field is sometimes referred to as "exogenous electrification." The polarity and location of the charges will, of course, depend on the relative orientation of the airplane and the electric field. This is illustrated in Fig. 19, which shows the induced charge distribution that would form when the airplane is under the influence of an electric field. One must keep in mind while examining Fig. 19 that the unshown third dimension of the airplane implies a three-dimensional pattern of induced surface charge and intensification of electric field by sharp projections.

The induced charge distributions formed on the airplane surface arise because the conducting electrons in the metal fuselage move freely under the influence of the electric field until the electrically induced regions of free charge on the airplane surface exactly balance out the external field and there is no residual electric field in the interior of the metal and fuselage. The metal of the fuselage is a sufficiently good conductor of electricity that the induced charge is formed in much less than a microsecond. In those portions of the airplane where the surfaces are nonmetallic, such as control surfaces and windows, the formation of induced charges occurs much more slowly. In the case of clean dry glass or plastic the time for the induced charge to form may be as long as minutes, but because of normal amounts of moisture and dirt, even the nonmetallic parts of the fuselage surface probably are fairly good conductors, so that the induced charges may be formed in only a fraction of a second.

The density of the induced electric charge on the airplane fuselage is proportional to the electric field; it is greatest at the extremities of the airplane and where the radius of curvature of convex surfaces is smallest. The wing tips, nose, tail surfaces, propellers, and projecting objects such as radar antennas, pitot tubes, etc. are the usual extremities having small radii of curvature.

### POINT DISCHARGE PROCESS

In an earlier section we discussed the ionization process known as point discharge, corona, or St. Elmo's fire that, when the electric field is intense, occurs from elevated structures on the earth's surface. The same process takes place from an airplane when, as the result of either autogenous or exogenous electrification processes, the electric field on the surface of the airplane becomes sufficiently intense. Where the intensity of the field is greatest, at the extremities of the airplane and the surfaces of small radii

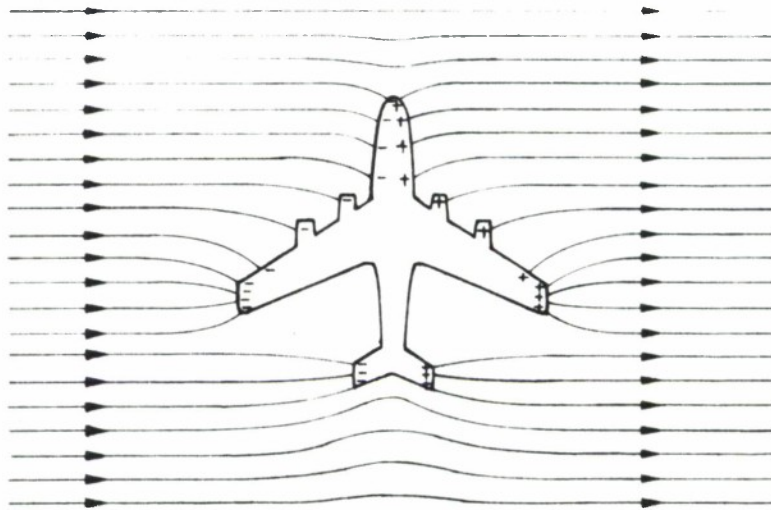


FIGURE 19 - Charges Induced on an Airplane Under the Influence of an Atmospheric Electric Field

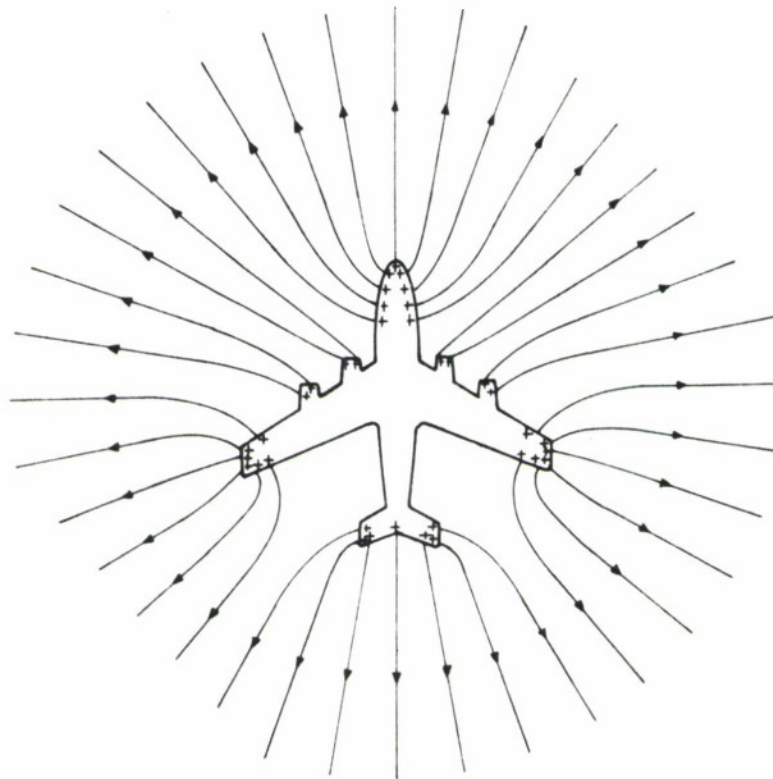


FIGURE 20 - Electric Field Produced by Net Charge on Airplane



of curvature, the air becomes ionized and conductive and the electric charges on the airplane surface begin to flow into the atmosphere.

Observations such as those of Stimmel et al. (1946) illustrated in Fig. 20 show that the corona current increases very rapidly with the electric field. As a consequence, the amount of charge or the intensity of the electric field on the airplane fuselage is limited even for energetic charging mechanisms.

The ions released into the atmosphere by corona or point discharge act to reduce the electric field at the airplane surface and in this way limit the current flow. If the air surrounding the airplane were not in motion, the charge released into the atmosphere would soon accumulate and limit the process to a small current. It is therefore apparent that the current that flows is proportional not only to the electric field but also to the air speed. The observations of Gunn et al. (1946) show that in the electric fields of the thunderstorm the point discharge current flowing from an airplane may reach 10 milliamperes. It is probable that in the case of the contemporary jet transport, which is larger and faster than the airplanes used by Gunn, the currents are even larger.

#### NET CHARGE OF AIRPLANE

Under the normal conditions of flight in clear air in fair weather the airplane is almost electrically neutral, carrying only a small amount of net charge. However, in some conditions it can become highly electrified with an excess of either positive or negative charge. A positively charged airplane and its electric field are represented in two dimensions in Fig. 21.

(A) Tire Electrification. Quite often the airplane may acquire an appreciable electric charge as the result of contact electrification between the wheels and the runway during takeoff. Usually such electrification is short lived, for in a matter of a few seconds it leaks off by conduction through the exhaust gases, which are moderately ionized and conductive.

(B) Point Discharge Electrification. The formation of point discharge from the extremities of an airplane in the strong electric field of a thunderstorm has already been described. In general the region of induced negative charge is quite similar to the region of induced positive charge, so approximately equal positive and negative point discharge currents flow and the airplane remains neutral. The point discharge currents do not always balance, however, for the characteristics of the positive and negative point discharge processes differ somewhat; because of this difference, more charge of one sign than the other may be released, and the airplane will thus acquire a net charge. Similarly, there may sometimes be an asymmetry between the location of the positive and negative regions of induced charge, and they may be on surfaces of widely different radii of curvature or of widely different air flow. Under these conditions one of the point discharge currents will be much larger than the other, and the airplane will acquire a net charge. The inequality of two point-discharge currents cannot exist for long, however, for as one sign of charge accumulates on the airplane it will increase the rate of point discharge of this polarity and decrease the rate of the other until equilibrium is reached.



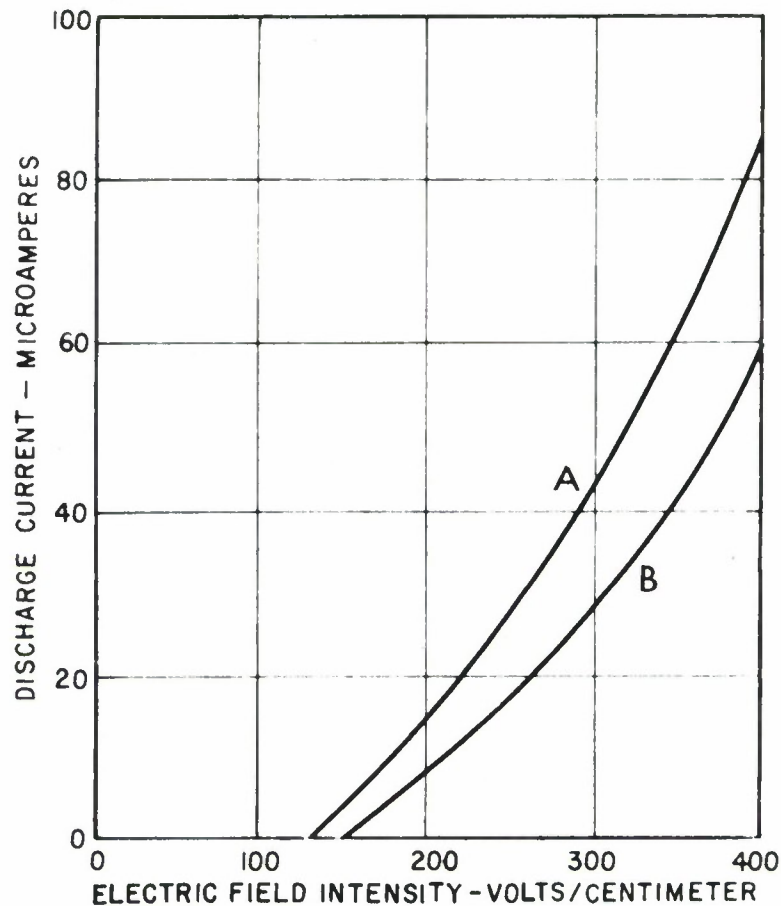


FIGURE 21 - Relationship Between Corona Discharge Current and Electric Field on the Belly of B17 Research Airplane from 1/4-inch Rod Extending Out One Foot from a Wing Tip, A, and the Tip of the Vertical Stabilizer, B. Airplane Charged Negatively. (Stimmel et al. 1946)

(C) Exhaust Electrification. The airplane can acquire charge as the result of the exhaust of its engines. Differences in the ion mobilities in the exhaust, contact electrification of particulate matter in the exhaust, and polarization of the exhaust plume under the influence of electric fields cause the exhaust to carry a net electric charge, and the airplane therefore acquires the opposite charge. In airplanes equipped to make electrical measurements it is observed that changes in the engine settings cause electrical perturbations that are sometimes large enough to interfere with the measurement of weak electric fields. This effect becomes small at high altitudes, presumably because of the increased electrical conductivity of the atmosphere.

(D) Electrification by Contact with Charged Particles. Another way that the airplane can become electrically charged is by collision with the charged precipitation or aerosol particles that sometimes occur in the atmosphere. Under these conditions the charge on the particles may be transferred to the airplane and accumulate there.

(E) Electrification upon Collision with Particles. Strong electrification usually results when an airplane collides with dust, precipitation or cloud particles.\* Although the details of physics of the process are far from well understood and are without doubt very complicated, there is no question that when two surfaces come into contact a transfer of charge takes place. Positive charge forms on one surface and an equal negative charge on the other. When the two surfaces are separated, they retain their respective charges and are strongly electrified. As the result of this process, airplanes flown in precipitation often acquire a high electric charge. In general it appears that flight through clouds consisting of small liquid water drops gives only weak electrification compared to rain. Snow or the ice particles in cirrus clouds produces a much more vigorous charging that often causes point discharge sufficiently intense to make a radio frequency noise that interferes with radio communications.

Stimmel's (1940) data, which was obtained with World War II medium and large bomber airplanes, indicates that the airplanes acquired electric charges of the order of millicoulombs as the result of the electrification that took place when the airplane flew through snow.

The charge carried on an airplane is determined by its electrical capacity, which is proportional to its size, and by the rate at which the airplane is acquiring charge and the rate at which it is losing charge. When the airplane is charged by collision with particles, the rate of charging will increase with its size and speed.

Undoubtedly the charges acquired by the present day commercial jet liner are somewhat larger, because these airplanes are larger and have a greater electrical capacitance. Furthermore, we may expect that the charging rates will be higher because of the modern airplane's greater size and speed. Stimmel's observations indicate that the rate of charging increases with speed in an exponential fashion. Some of his observations show the electrification depending almost on the fifth power of the speed.

Probably the rate at which charge leaks off a modern airplane is greater too, partly because of its greater size and partly because of the greater air speed carrying the point-discharge ions away.

#### ELECTRICAL EFFECT OF AN AIRPLANE ON A THUNDERSTORM

We have seen from the foregoing discussion that the charge that can exist on the surface of an airplane is limited by the dielectric strength of the air. When charge appears on the surface of the airplane, either by induction in the electric field of a storm or by contact electrification, the electric field increases until the point is reached that dielectric breakdown occurs and the charge begins to leak off. As a consequence, the maximum charge that can accumulate on even a large modern airplane is limited to a small fraction (probably not more than a hundredth) of a coulomb.

\*Contact electrification may be either positive or negative depending upon the composition of impacting particles. Ice striking against a clean aluminum surface deposits negative charge, but if the airplane has a painted or waxed surface the deposited charge may be positive.

The electric charge in a storm, as we have seen, may amount to tens or hundreds or thousands of coulombs, which is many orders of magnitude larger than the charge on the airplane. Since the electric field varies inversely as the square of the distance from a charge, the electric field perturbation produced by the airplane is small compared to that from the cloud, except near to the airplane. Let us now examine how the airplane may affect the electrical variables of the thunderstorm.

(A) Intensification of Electric Field as the Result of Induced Charge. When electric charge flows in the airplane and accumulates on its surface as the result of the electric field of a thunderstorm, it greatly intensifies the thunderstorm field. At the exposed sharp surfaces of the airplane such as the wing tips, extremities of the empennage, and exposed radio antennas the induced charges may increase the existing field of the thunderstorm by several orders of magnitude. As the result of this field concentration effect, the highest electric fields in a storm are often at the surface of an airplane flying in it.

The intensification of the strength of the electric field described above would take place even if the dimensions of the airplane were negligibly small with respect to the dimensions of the region of strong electric field in the thundercloud. Sometimes the dimensions of the airplane can be as much as five percent of the length of a lightning stroke; because the airplane is a good conductor, it might further reduce the potential differences required for lightning by causing a slight but possibly significant reduction in the required length of the ionization path.

To be sure, the greatly intensified electric field at the airplane is of limited extent. Because equal and opposite charges are produced by induction on the airplane fuselage, the electric field perturbations produced by the two opposite charges oppose each other and nearly cancel each other out at a distance of only a few airplane lengths or wing spans away.

(B) Modification of the Electric Field as the Result of Net Charge on the Airplane. When a net charge is carried by the airplane, the electric field produced by this charge will be added to the electric field produced by the induced charge. It will therefore act to increase even further the electric field of the induced charge of the same polarity, but it will reduce the field of the opposite polarity. As a result, if the electric fields at the airplane surface become intense, corona will occur preferentially in the region where the induced and net charge intensify each other and will therefore tend to remove the net charge on the airplane.

Induced charge is in the form of a dipole, and the electric field that it produces is inversely proportional to the cube of the distance from the airplane. The net charge, being a monopole, produces a field that varies inversely as the square of the distance, so its effects will not attenuate as rapidly.



(C) Modification of Electric Field as Result of Space Charge Release.

Because charge is conserved, whenever an airplane acquires charge of one polarity, an equal and opposite charge must be released into the atmosphere. Therefore, when an airplane becomes charged by point discharge or by contact electrification, it leaves behind a charged cloud of ions, cloud particles or dust, as is illustrated schematically in Fig. 22. When the airplane reaches its equilibrium charge, at which the charging processes are balanced by the discharging processes, though the airplane still may be leaving behind charged particles of one sign by a process such as contact electrification, it is also leaving behind an equal and opposite amount of charged ions by point discharge. Because the airplane moves rapidly and because the charged particles rapidly migrate into the atmosphere, the charged cloud released by the airplane is diffuse and is hence much larger than the airplane. The electric fields resulting from the cloud are therefore less intense than those produced by the airplane. Since the unipolar charge released by the airplane can be no larger than that acquired by the airplane, the charged cloud produced in this way will also be limited to ten millicoulombs or so and will be small compared to the far larger charges in the storm.

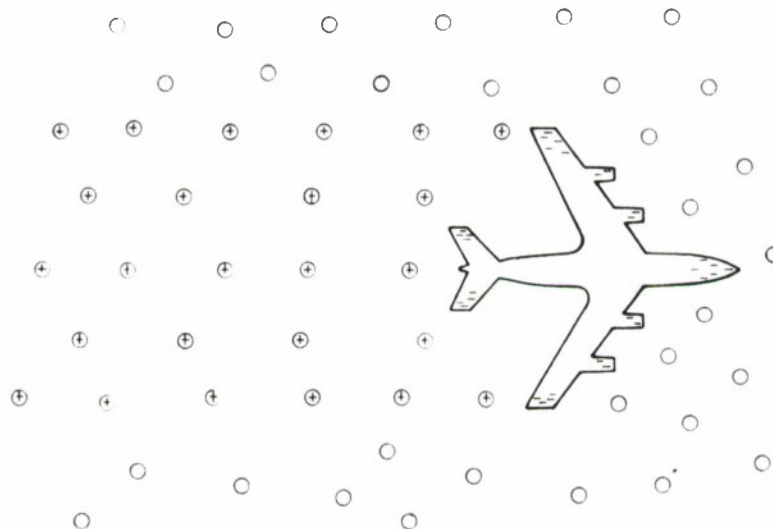


FIGURE 22 - Airplane Colliding with Cloud or Aerosol  
Particles Acquires One Sign of Electric Charge  
While the Particles Acquire the Opposite Sign of  
Charge

When the electric field is intense, as the airplane flies along it can emit by point discharge a cloud of positive ions from one wing tip and a cloud of negative ions from the other at rates approaching one coulomb per minute. This process is illustrated schematically in Fig. 23 for the case in which the electric field is horizontal and nearly at right angles to the direction of flight.

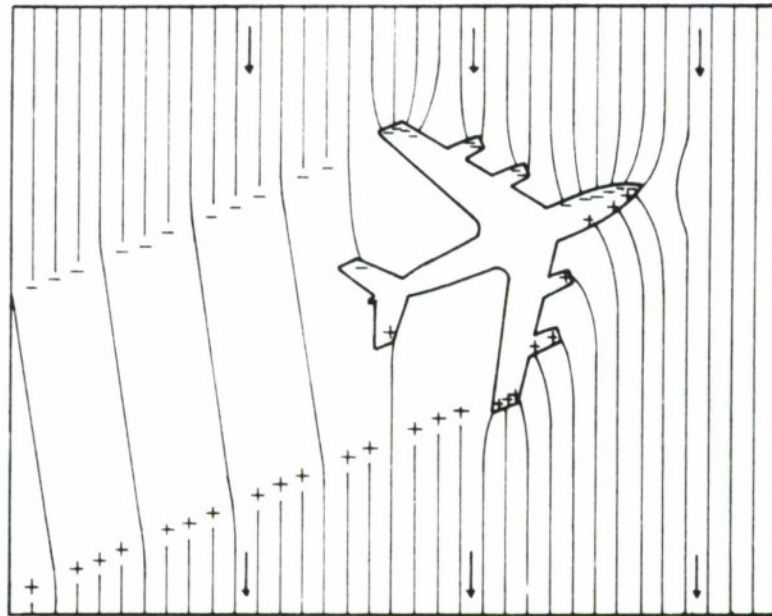


FIGURE 23 - When the Airplane Goes into Point Discharge Under the Influence of a Strong Field, Positive and Negative Ions are Simultaneously Released into the Atmosphere from Opposite Points on its Surface

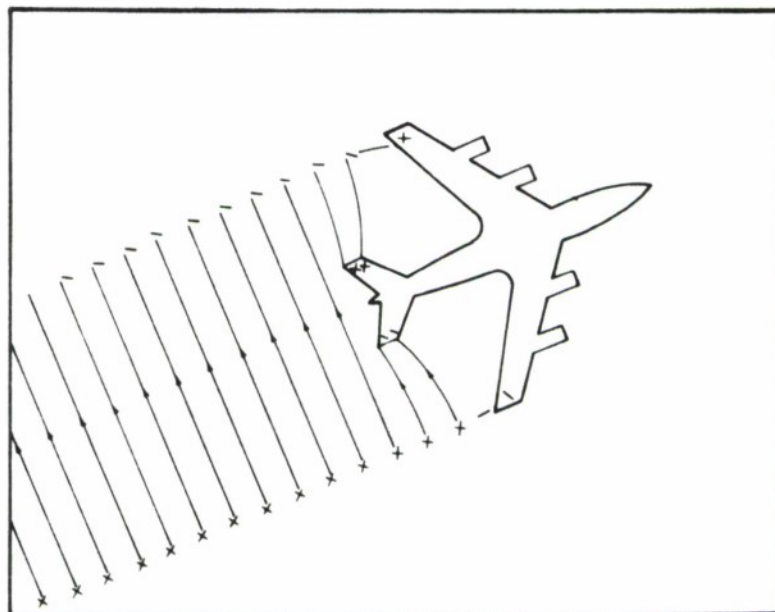


FIGURE 24 - If the Atmospheric Electric Field Suddenly Drops to a Low Value, as it can Under the Influence of Lightning, a Strong Field May be Produced

There has been little or no investigation of the behavior of the clouds of space charge produced by airplanes in or near thunderstorms, so we are forced to speculate about what happens on the basis of our knowledge of electrified particles. If the airplane is flying in clear air near the storm, the fast ions being released may persist for some time and may move with considerable speed. The mobility of the ions is of the order of a few  $\text{cm sec}^{-1}$  per  $\text{v cm}^{-1}$ , so the ions in the two clouds of opposite polarity would separate at a rate of about  $100 \text{ m sec}^{-1}$  in a field of  $3 \times 10^3 \text{ v cm}^{-1}$ . If lightning caused the field to reverse suddenly, the direction of motion would reverse and the ions would approach each other.

If the airplane is flying in a cloud, the fast ions produced by corona will become rapidly attached to cloud particles, and as a consequence their mobility will be greatly reduced. Inside the cloud we may expect that the regions of space charge produced by the airplane might persist longer than they would in the free air.

It is interesting to note that the space charge produced by point discharge from the airplane will create a region behind the airplane where the electric field of the storm may be considerably reduced. As shown in Fig. 23, the lines of force of the storm terminate on the space charge, and between the streams of charge the field is reduced. If the field of the storm relaxes or changes direction, as it often does, there may be a high field between the space charge streams, as is shown in Fig. 24.

(D) Modification of Electrical Conductivity as Result of Ion Release.  
Thus far we have considered the effect of the charge carriers introduced into the atmosphere in terms of their space charge effects. It is worth noting that the charged particles produced by the airplane will have an appreciable effect on the ion population in the atmosphere and on its electrical conductivity. A point discharge current of  $10^{-2}$  ampere corresponds to the introduction into the atmosphere of  $6 \times 10^{16}$  ions per second, which is somewhat larger than natural ion production rate per cubic kilometer of atmosphere at sea level. It is therefore to be expected that the passage of an airplane could make appreciable changes in the electrical properties of the atmosphere in or near a thunderstorm.

#### RELATIONSHIP BETWEEN AIRPLANE AND OCCURRENCE OF LIGHTNING

There is so little information concerning the density of lightning in the flight path of airplanes that it is difficult to determine whether or to what extent the presence of an airplane may increase or decrease the likelihood of a lightning discharge. In the absence of this knowledge we must approach the problem on the basis of our present rather limited knowledge of thunderstorm electrification and the lightning discharge. In this section we will discuss some of the possible relationships between airplanes and the occurrence of lightning.

Even if airplanes had no effect whatever on lightning, one would still expect that they would be struck on the basis of chance. When an airplane is flying in or near a thunderstorm, it is certainly possible that the airplane will find itself in the path of a developing lightning spark or that



the airplane will fly into the electrical discharge. In this event it is conceivable that the trajectory of the lightning spark might be unaffected by the presence of the airplane.

We can make some rough estimates of the chance that an airplane might intercept a lightning stroke on the following basis: According to Hagenguth (1951), the density of lightning strokes per year per square mile is approximately one half of the number of storm days per year for a given area. If we use an average value of 50 storm days per year, we would expect on the basis of Hagenguth's approximation that 25 strokes would occur per square mile per year or, in other units, a density of  $10^{-3}$  strikes  $\text{km}^{-2} \text{ hr}^{-1}$ . We can estimate the effective cross section of the airplane to be  $10^{-2} \text{ km}^2$  on the basis that the airplane is moving  $200 \text{ m sec}^{-1}$ , has a wing span of 50 m, and that the lightning stroke might last as long as one second. With these assumptions one would expect the airplane to have a strike frequency of  $1 \times 10^{-5} \text{ hr}^{-1}$ .

This calculation gives a value more than an order of magnitude smaller than the actual strike frequency as reported by Newman (1963) of  $3 \times 10^{-4}$  strokes  $\text{hr}^{-1}$  for propeller airplanes,  $2 \times 10^{-4}$  strikes  $\text{hr}^{-1}$  for turboprop airplanes and  $1 \times 10^{-4}$  strikes  $\text{hr}^{-1}$  for pure jets. When it is taken into consideration that pilots usually are successful in avoiding flight through thunderstorms, this calculation indicates that the presence of an airplane may increase the probability of a lightning stroke. This conclusion is subject to considerable doubt for several reasons. For example, Hagenguth's approximation relates to cloud-to-ground strikes and ignores cloud-to-cloud discharges. The airplane is, of course, often vulnerable to this type of discharge, whose frequency may be an order of magnitude higher than the cloud-to-ground strike. Furthermore, this calculation was based on the assumption that the sparks of the discharge followed a single vertical path from the cloud to a point on the ground.

While this may be a reasonable assumption in the clear air, it probably is not inside the cloud. Here, because the discharge is shielded from view, we know very little about its shape. By analogy we might assume that it is similar to the discharge pattern shown in Fig. 25, which was made in a highly charged block of methyl methacrylate. If the discharge pattern in the cloud is similar to this, the airplane flying through the cloud might encounter a situation similar to that shown in Fig. 26, and its chances of intercepting lightning would be very high. To be sure, if this is the case, the quantity of charge carried by the individual branches of the discharge would be far less than that carried by its main trunk.

(A) Fortuitous Association. Newman (1963) has considered one of the ways that an airplane could become involved as part of the conducting path of a lightning flash as the result of a fortuitous encounter in or near to a thunderstorm. Fig. 27 is a reproduction of Newman's drawing showing a possible sequence of events. According to this picture, when the stroke makes contact, the aircraft "potential is immediately raised to 50 to 100 million volts and streamers now emanate from all aircraft extremities..."



FIGURE 25 - Pattern of the Electric Discharge in a Block of Methyl Methacrylate that has been Bombarded with Electrons Accelerated through a Megavolt Potential Difference

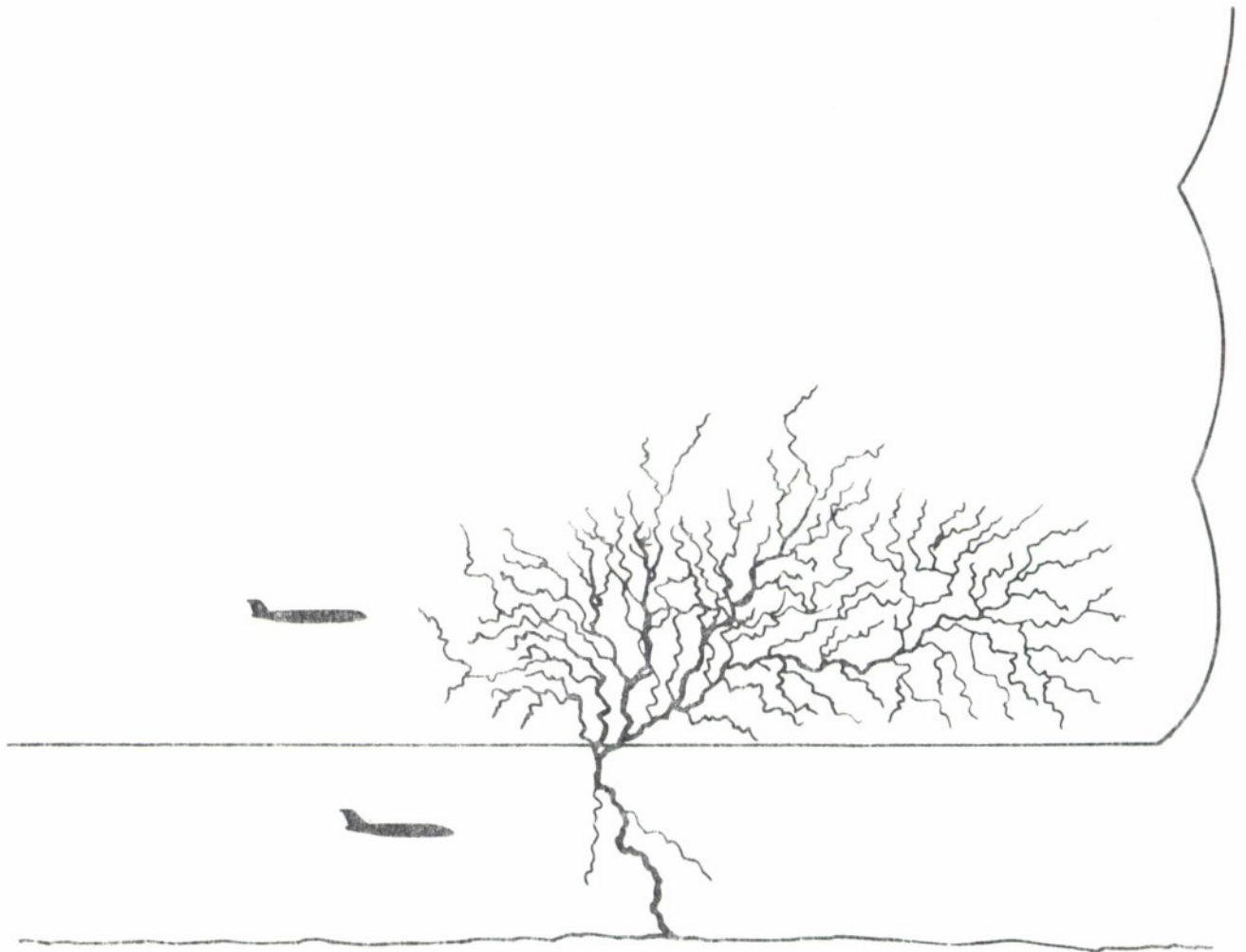


FIGURE 26 - Possible Structure of the Lightning Discharge Inside the Thundercloud



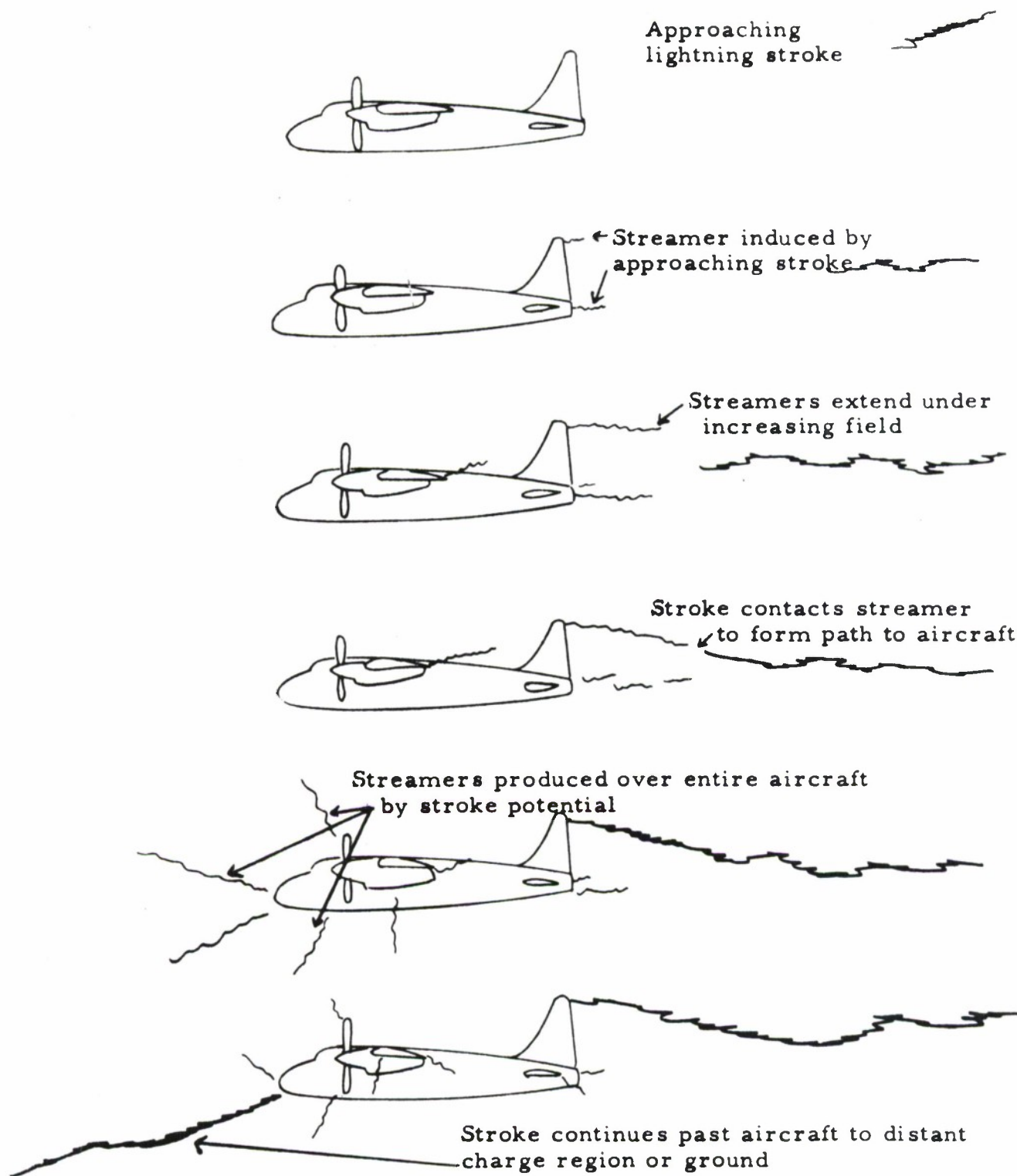


FIGURE 27 - Mechanism of Lightning Stroke Approach to Aircraft, Illustrating Streamer Formation at High Gradient Points or Extremities of Aircraft According to Newman (1963)

An alternative to Newman's explanation appears possible, as is shown in Fig. 28 in which, simultaneous with the formation of the streamer toward the advancing stepped leader, a new stepped leader begins to form on the opposite part of the airplane and continues the development of the discharge. If this were the sequence of events, it appears possible that any streamers from the airplane might be less intense than according to Newman's ideas.

Because the time duration of the stepped leader is usually but a small fraction of that of the total discharge, and because the airplane can move many fuselage lengths during the discharge, it is more probable that the airplane will fly into a discharge than that the advancing stepped leader will contact the airplane. If the airplane flies into the discharge, it could do so during any of the following stages: the stepped leader, the return stroke, the continuing current, or the dart leader. In this event it appears that the metallic fuselage serves a part of the conducting channel, with the current entering at one point and leaving at another.

(B) Effect of Airplane's Electric Field on Path of Lightning. Data on the frequency of lightning strikes to various portions of airplanes show that some parts of the airplane are far more likely to receive a lightning stroke than others. For example, Newman's data (1963) on pure jets shows that exposed portions such as the vertical fin, wing tips, nose, antennas, and elevators receive 80% of the lightning discharges as compared with only 15% for the fuselage. This sort of distribution is not what would be expected on the basis of chance and strongly suggests that, at least over distances of the order of its dimensions, the airplane is having a significant effect on the path of the lightning discharge.

Those portions of the airplane experiencing the highest frequency of lightning discharges are convex extremities with a small radius of curvature, where the electric field is most intense. It therefore appears what the charge which is concentrated on these exposed parts of the airplane has a significant effect on the lightning.

One way that this might happen, which we have already discussed, is that under the influence of the electric field the lightning discharge might propagate toward the airplane. This could take place as the result of the action of the field of the airplane on the direction taken by the leader, by the formation of a streamer discharge that originates on the airplane and extends out to meet the advancing leader, or by the initiation of the lightning by the airplane.

(C) Initiation of Lightning by Airplane. There is evidence to suggest that under some conditions the airplane may serve to initiate the formation of a lightning discharge. Faucher and Curtis (1958) cite the observations that of the airplanes struck by lightning only 45% of the cases report other lightning before or after the discharge involving the airplane. They interpret this to mean that the airplane may be triggering the lightning.

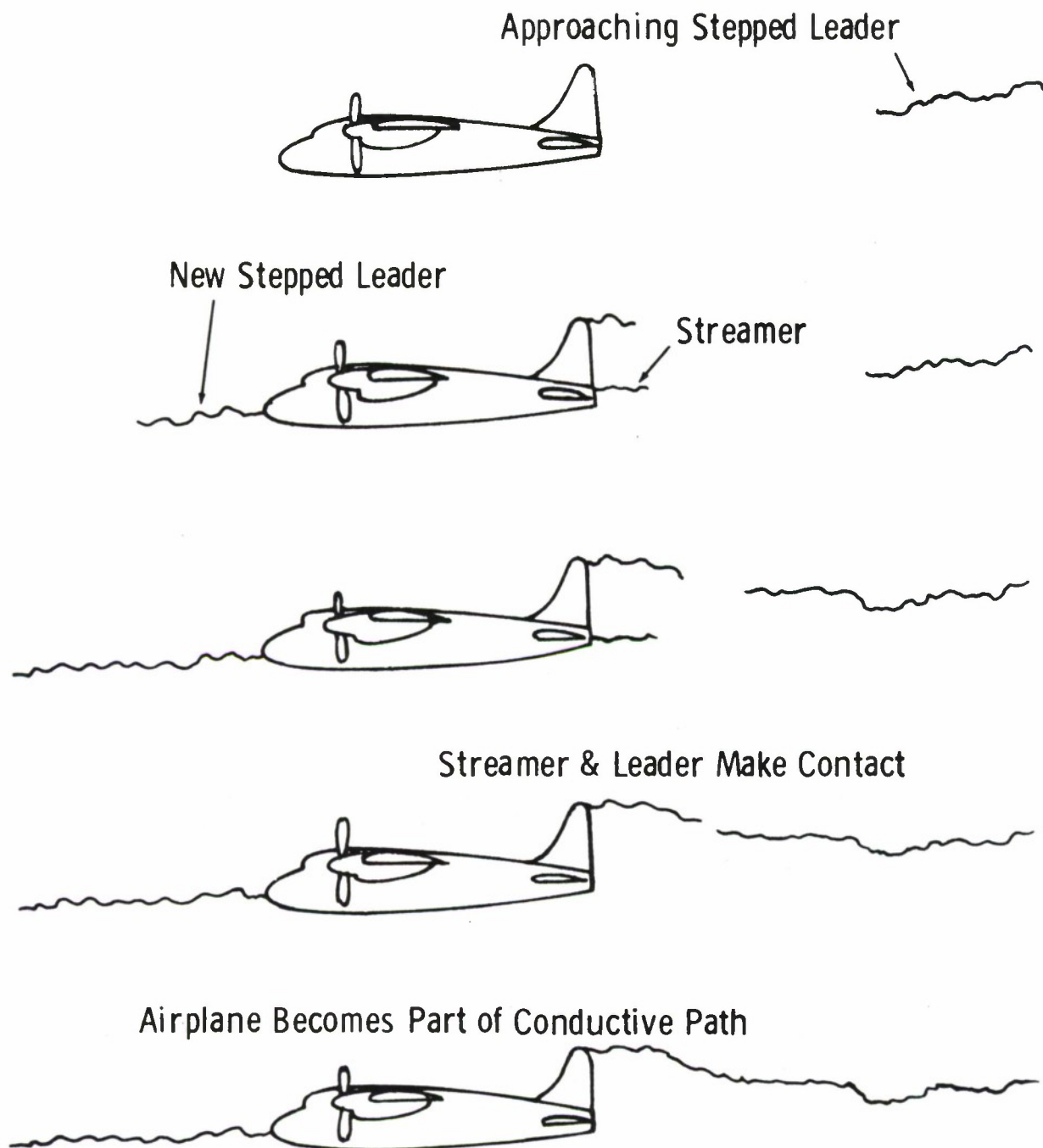


FIGURE 28 - Alternative Sequence of Events to that Proposed by Newman for Interception of Airplane by Lightning



With few exceptions, very nearly all lightning discharges originate in the clouds, and it is generally believed that the lightning process is initiated here by the electrical field intensification occurring at water drops or ice crystals. Since the electric field intensification produced by the airplane is larger than that occurring naturally, it is reasonable to suppose that the airplane might initiate a lightning discharge.

As we have discussed earlier, lightning discharges can be triggered by the sudden introduction of a conductor into the electric field of a thunderstorm, as for example by the rising plume of water from a depth charge illustrated in Fig. 18 (see Brook et al., 1961 and Young, 1962). Recently Newman (1964), using a technique similar to that suggested by Boys (1926, 1927), has succeeded in triggering a lightning discharge by firing under a thunderstorm a rocket which trailed behind it an electrically grounded wire.

The observations of McEachron (1939, 1941) show that tall structures such as the Empire State Building can unquestionably trigger a lightning discharge by initiating the formation of a stepped leader. Although, as is illustrated in Fig. 29, the dimensions of an airplane are small when compared to the Empire State Building, it must be recognized that because the electric field is much larger near the cloud than it is on the ground, the airplane may have a larger effect than is indicated by its size. If, as is indicated in Fig. 30, we compare the potential spanned by the Empire State Building and its mirror image with the potential spanned by the airplane, we see that their effect in intensifying the field can be of the same order of magnitude.

On the basis of our present rather fragmentary evidence, there are reasons to believe that airplanes may trigger lightning and that this phenomenon may occur with sufficient frequency to be of importance. Fig. 31 illustrates how in a strong electric field an airplane might initiate the formation of a discharge. Since the airplane can carry no more than a few millicoulombs of charge, far less than that carried by a stroke, it appears that the triggering of the discharge would take place by the simultaneous formation of two stepped leaders proceeding from the airplane in opposite directions. One of these leaders would advance outward from an area of negative charge and would possibly resemble the normal stepped leader of the onset of a lightning flash to the earth. The other would advance away from an area of positive charge. The detailed ionization processes and mechanisms of advance are apt to be quite different in the two cases.

(D) Effect of Aircraft Motion on the Lightning Discharge. The interactions between an airplane and a lightning discharge are considerably complicated by the high speed of the airplane relative to the atmosphere in which the ionized path of the lightning discharge is established. There are few if any direct observations (such as photographs) to indicate what kinds of phenomena take place, so it is necessary to offer tentative speculations based on limited evidence.

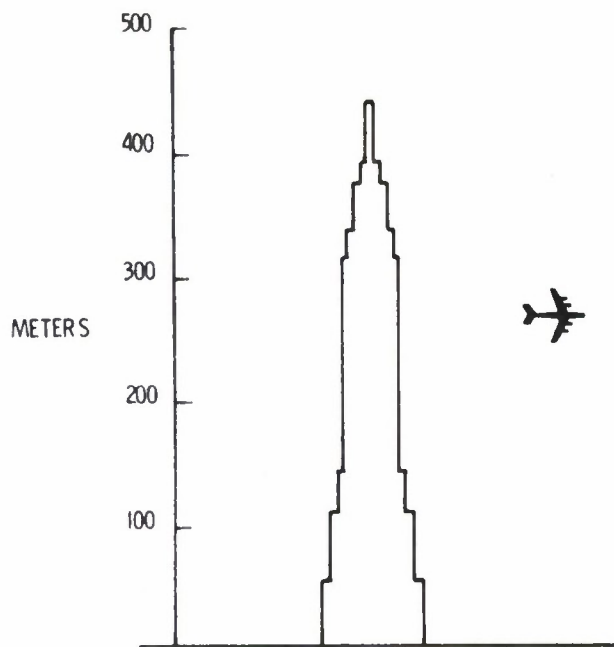


FIGURE 29 - The Size of a Jet Transport is of the Order of One-tenth That of the Empire State Building

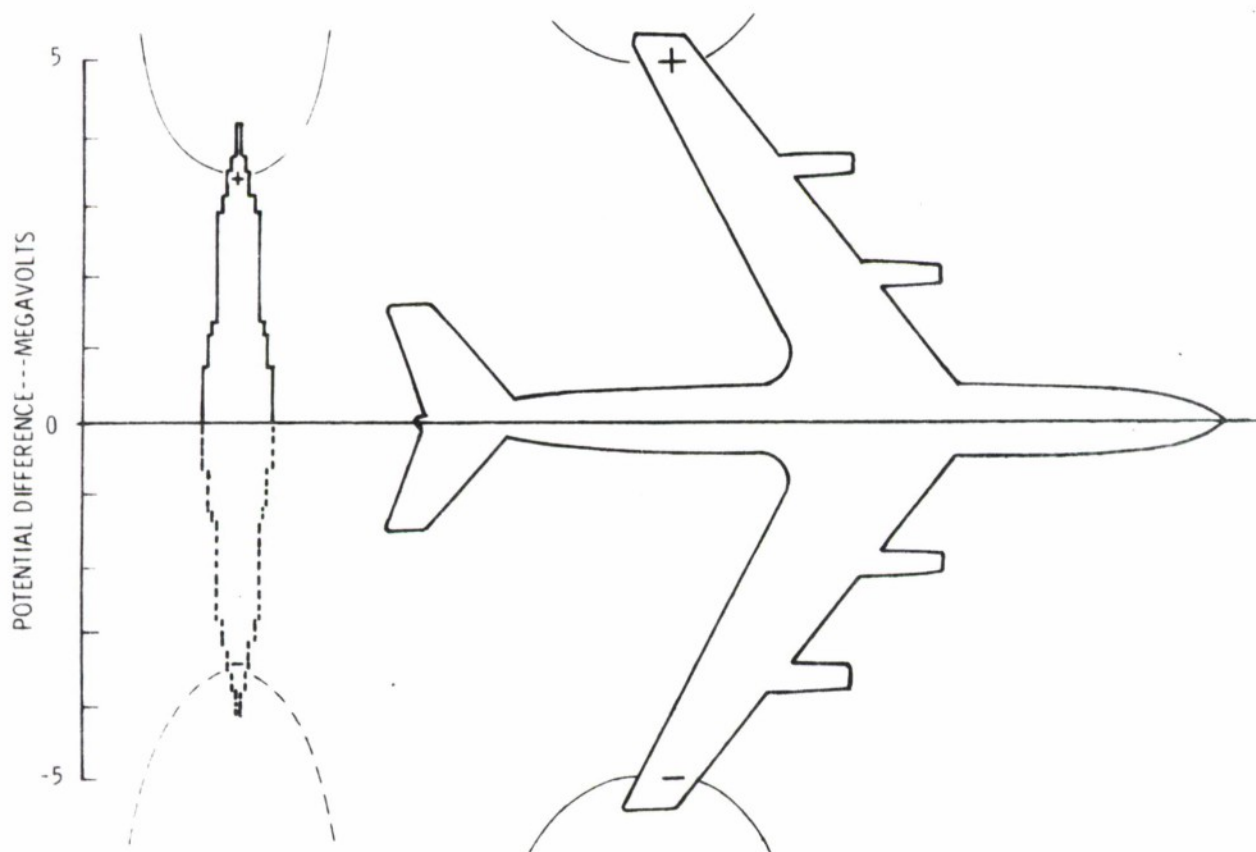


FIGURE 30 - Because the Electric Field Aloft is Much Higher Than It is Near the Ground, the Potential Spanned by a Jet Transport in a Storm is Comparable to That Spanned by the Empire State Building and Its Mirror Image

One possible interaction between the airplane and the lightning is that case in which the airplane initiates the formation of the stepped leader, as is shown in Fig. 31. This process presumably may begin as corona or St. Elmo's fire at the extremities of the airplane that then continues to propagate as a leader if the electric field is sufficiently high. It seems quite probable, since the speed of air motion over the airplane is comparable with the velocities of ions in a thunderstorm field, that the movement of the airplane will have an appreciable effect on the initiation of a discharge. In the absence of any data, we may guess on this basis that probably the air motion will act to quench and suppress the discharge, so that perhaps the speed of the airplane acts to inhibit the initiation of lightning. This conclusion is by no means certain, however, for the laboratory experiments reported by Brook et al. (1961) show that in the case of a fine wire electrode, rapid motion suppresses the action of corona; this in turn, tends to reduce the electric field and favors the formation of sparks.

Another effect that results from the aircraft motion is the appreciable pressure lowering that occurs in some regions of the air flowing over the airplane and in the vortices that the airplane produces. Since the potential difference required to produce a spark is known to be proportional to the atmospheric pressure, we may expect that the development of a lightning discharge might be facilitated in these regions of low pressure.

As we have discussed earlier, the lightning discharge is far from instantaneous and often consists of multiple strokes, current surges, or continuing currents that sometimes may last a second or longer. A jet transport aircraft can move many fuselage lengths in this period of time, and the question arises, to what extent will the airplane move relative to the ionized lightning channel and to what extent will the ionized lightning channel move along with the airplane? The available evidence suggests that there is no simple answer to this question and that the phenomena are complicated and variable.

In many cases when a lightning discharge passes through an airplane the damage is found to consist of a series of pits or holes melted or vaporized in the metal skin that are oriented in a line along the direction of flight (Newman et al. 1963). This evidence strongly suggests that the pits or holes were produced by strokes or current surges as the airplane moved relative to the ionized path of the lightning discharge.

The most commonly observed time interval between strokes is about 20 to 50 milliseconds, according to Malan (1963); hence, one might expect if the airplane velocity were of the order of 100 to 200 m sec<sup>-1</sup> that the separation between pits on the fuselage should be about 2 to 10 meters. Actually the observed separation of pits is commonly only a fraction of a meter, indicating that the relative velocity between the airplane and the ionized lightning path is only a fraction of the airplane speed. This suggests that the relative velocity of the airplane and the lightning may be determined by the boundary layer conditions.

In Fig. 32 we show, with the airplane as our frame of reference, how the successive strokes of a lightning spark to the forward part of the fuselage might be carried aft by the moving air.



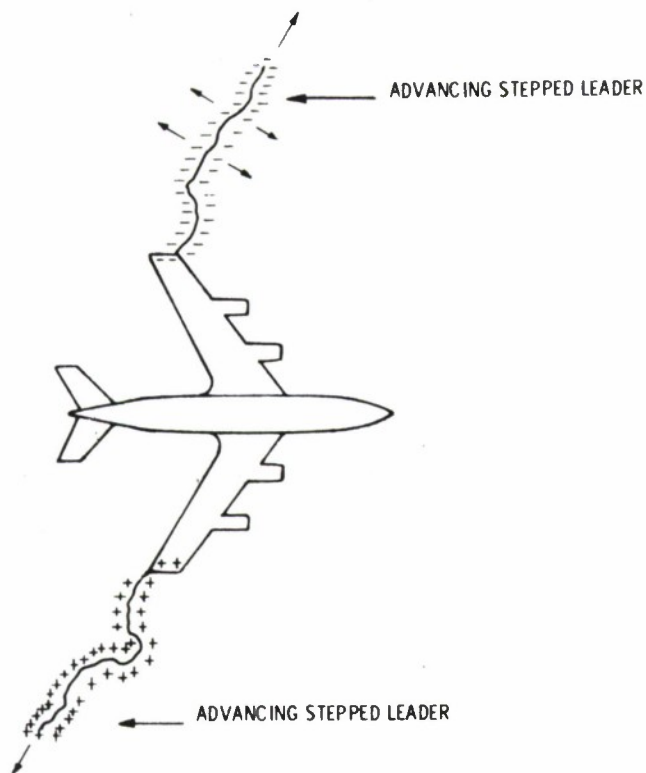


FIGURE 31 - How an Airplane Might Initiate a Lightning Discharge in a Region of Strong Electric Field in or near a Thundercloud

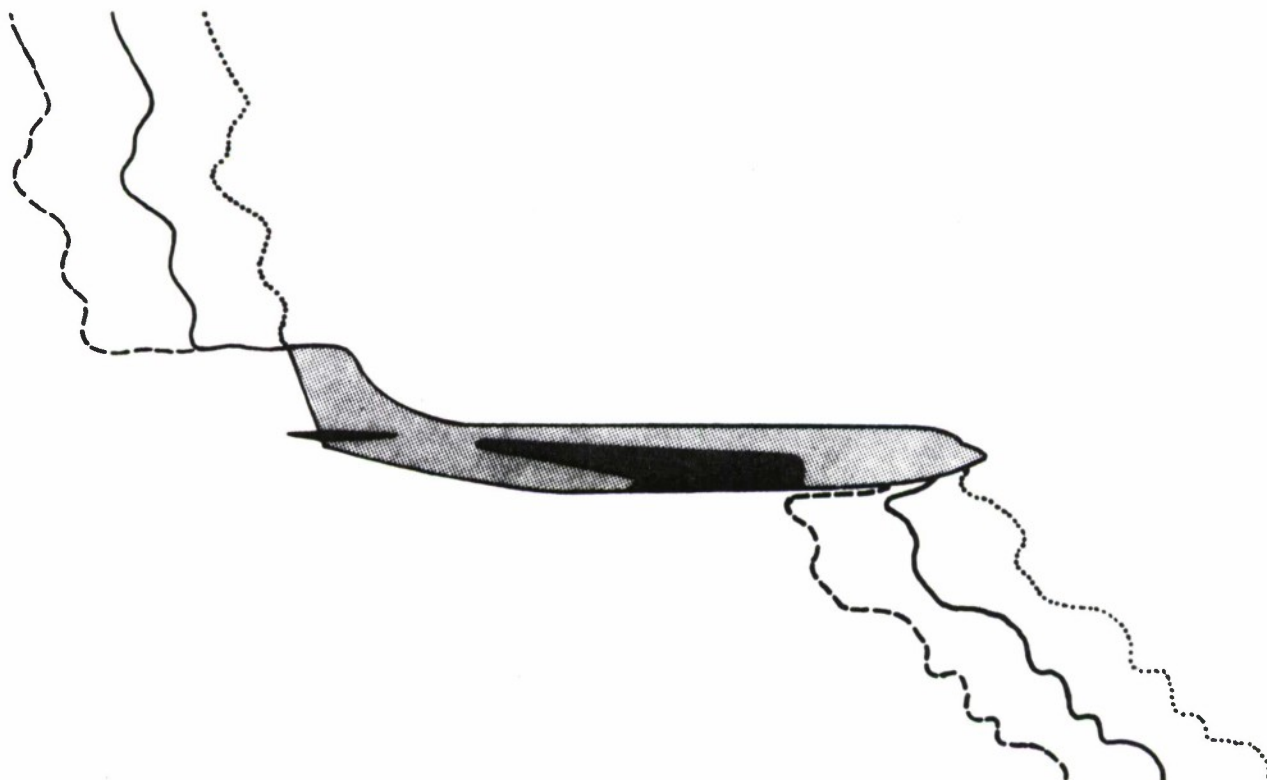


FIGURE 32 - Diagram with Airplane as the Frame of Reference Showing How Successive Strokes are Swept Back Along the Fuselage by the Flow of Air. (Because of boundary layer effects the ionized path at the surface of the fuselage is swept back at somewhat less than airplane speed.)

Several kinds of evidence suggest that under some conditions the lightning discharge may move along with the airplane and continue to make contact with its surface at the same point. Newman (1953) has reported that the most intense damage to airplane wing tips is often at their trailing edge. This suggests that the airplane may move relative to the individual strokes but that when the discharge reaches the trailing portion of the wing it does not become detached, but "hangs on" and remains in the same position. In this case multiple strokes would pass through the same spot, and greater damage would result.

In recent studies Newman has shown experimentally that to duplicate some lightning damage to airplanes, it is necessary to use a discharge carrying of the order of hundreds of coulombs. Since individual strokes rarely carry over a few coulombs, it seems probable that this kind of damage must be caused by many strokes of lightning that move with the airplane and pass through it at the same point. Fig. 33 illustrates how successive strokes of lightning might take the shortest path by propagating toward the moving airplane and thus "follow" it along.

If an airplane has a very small wing span and a very high rate of speed, and if the continuing current between strokes were insufficient to maintain ionization, it is possible that only one stroke of a multiple-stroke discharge might pass through the airplane. Fig. 34 shows how if the airplane is sufficiently fast it might leave the discharge behind.

(E) Effect of Space Charge Released by Airplane on Lightning. We have already pointed out that in regions of intense electric field the airplane will in only a few seconds release into the atmosphere by point discharge more charge than it can carry on its surface. Malan (1963) and others have suggested that the detailed course of the lightning stroke is often largely determined by the distribution of space charge in the atmosphere. It therefore appears reasonable to believe that the space charge released by the airplane may in some cases initiate the lightning stroke or alter its path. The initiation and course of a lightning stroke are such highly variable phenomena that it would be quite a difficult matter to analyze them to determine how large an effect they would have on the likelihood of the airplane's being struck.

It is possible that space charge released from an airplane by point discharge may, under some conditions, reduce the likelihood of a lightning stroke. We have already discussed how this space charge can reduce the electric field at the airplane surface. It is therefore quite possible that this effect might reduce the frequency of the lightning near the airplane and along the aircraft wake. Again, the problem is highly complicated and difficult to resolve experimentally.

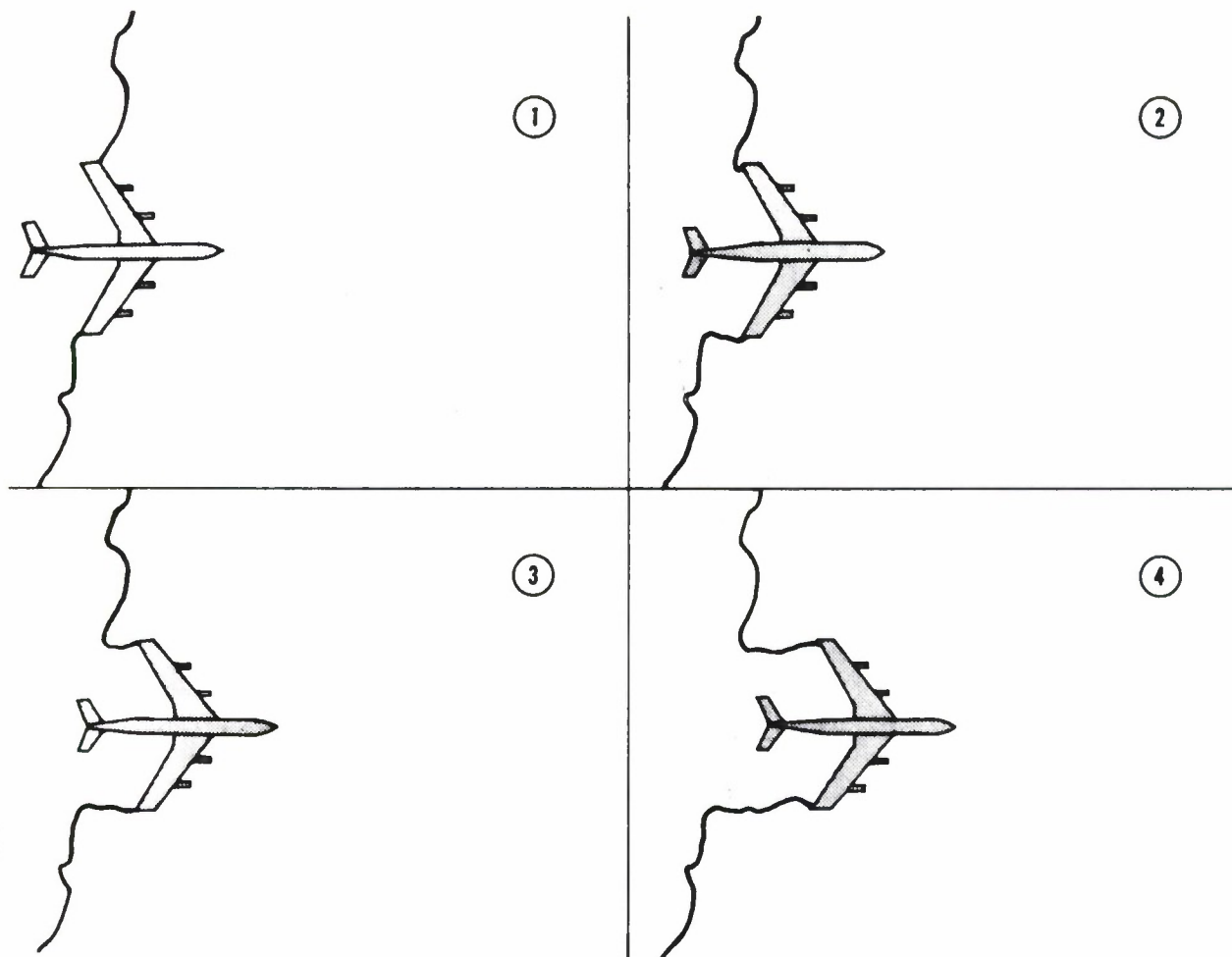


FIGURE 33 - Diagram with Lightning Discharge as the Frame of Reference, Showing How Successive Strokes Might Establish Ionized Paths That Allow Current to Pass Through the Airplane

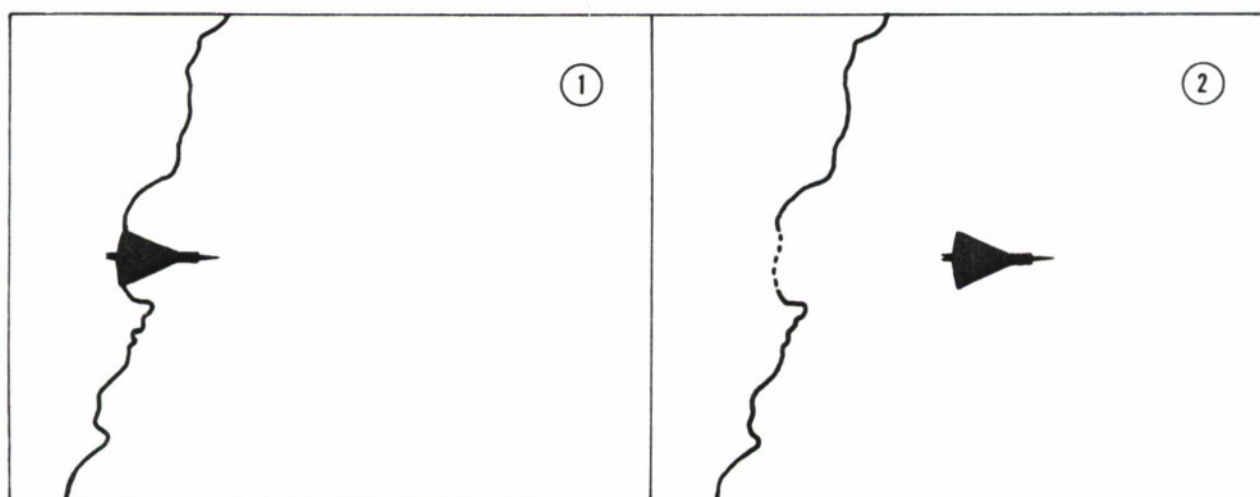


FIGURE 34 - Diagram with Lightning Discharge as the Frame of Reference, Showing How a Fast, Small Airplane Receiving One Stroke May Move Far Enough So That It Does Not Receive the Next Stroke



(F) Effect on Lightning of Ions Released by Airplane. Under some conditions it is possible that the ions released by the exhaust of the airplane and by point discharge may have an effect on the initiation of lightning and on the path that the spark takes. Some investigators have suggested that perhaps the ions in the exhaust trail may provide a conducting path that lightning will follow to the airplane.

In the author's view this appears unlikely, for this ionization is quite weak and the conductivity is so low that the electrical relaxation time is probably long compared to the time period involved in lightning. In fact we see that even after a period as brief as a second the very intensely ionized path produced by lightning itself has disappeared to the extent that it has no effect on the course of subsequent discharges.

### INFLUENCE OF NEARBY AIRCRAFT

All of our discussions thus far concerning the behavior of an airplane in or near a thunderstorm have been based on the assumption that if other airplanes were also present they were far enough away to have no effect. Although there is apparently little information concerning the electrical effects that one airplane can exert on another, there are reasons to believe that such effects do exist and in certain cases might be important. In this section we will attempt to extrapolate from the effects produced by one airplane to those which would result from two or more.

For the purposes of this discussion it is convenient to consider two cases: in the first the airplanes are flying in close formation, so that the distances between them are comparable with the size of the airplane; in the second the airplanes are separated by distances many times greater than the size of the airplane.

(A) Airplanes Close Together. When airplanes fly close to each other, as they do in formation, so that the distance of separation is a wingspan or less, there will be a considerable electrical interaction between them. The electric fields set up by each as the result of exogenous and autogenous charge will frequently add to each other and thereby cause an intensification in the electrical field that is larger than would be produced by one airplane alone. As the result of this field intensification we may expect that in some cases current may flow from one airplane to the other through point discharge or electric sparks. While such processes will reduce the electric field between the airplanes, it will increase the field at its outer extremities.

As the result of these processes it appears that several small airplanes can produce a large field perturbation comparable to that which might be expected from a much larger airplane. It appears reasonable to expect that when there are two or more airplanes together they will be more likely to initiate a lightning stroke than a single airplane alone. In the event that a lightning spark is initiated by one airplane or passes through it by chance, the field intensification that is caused by any other airplanes nearby will make them attractive targets, and we may expect that the spark will probably jump to them too.

In the event that an airplane is flying near to the ground, the effects of its electrical image will be equivalent to that caused by another airplane and can be appreciable. Probably the chances of being struck by lightning are therefore somewhat greater during landing and takeoff.

(B) Airplanes Far Apart. If the airplanes are separated by distances large compared to their wingspan, the effects caused by the interaction of their electric fields should be small. Accordingly, one might expect that a lightning stroke that had passed through one airplane would be unlikely to pass through another. It is therefore somewhat surprising to find an incident reported in which a flight of three aircraft were struck simultaneously in spite of the fact that the outer two aircraft were separated by an estimated half mile (Alexander 1956).

It is conceivable that under some conditions when dielectric breakdown occurs at one point in the cloud that the rapid field change may initiate breakdown at several other points where the field is concentrated, so that connected or possibly separate discharges may simultaneously involve several airplanes.

Under some conditions the presence of one airplane might be expected to reduce the probability of a strike to another. For example, if two or more airplanes are flying along in the same direction, one somewhat behind the other so that the first airplane encounters strong electric fields well in advance of the second, we may expect that the lead airplane might well trigger off a lightning stroke. If the following aircraft then flies through the same approximate region of the storm where the lightning occurred after a time period short compared with the average time interval between strokes, we may anticipate that its chances of receiving a lightning stroke would be appreciably reduced.

Since the time between lightning discharges in many storms is 10 seconds or less, and since the dimension of the lightning-producing region is probably of the order of 1 km, it appears under some conditions that it might be possible to provide some protection to one airplane by flying another airplane just ahead of it at an appropriate distance. For example, if the airplanes are flying at  $200 \text{ m sec}^{-1}$  and separated by 1 km, the first airplane would trigger off the stroke and by the time that the next stroke occurred the second airplane might be clear of the danger.

The feasibility of this sort of lightning protection is dubious at best, because in order to apply it effectively one would require more knowledge of the storm's structure and behavior than is usually available.

## POSSIBLE METHODS FOR PREVENTING LIGHTNING DISCHARGES TO THE AIRPLANE

### NONCONDUCTING AIRPLANE

We have seen from the foregoing discussions how electric charge can build up on an airplane and how the electric fields around the conducting airplane fuselage probably make the airplane more likely to be struck by lightning. To a large extent this difficulty might be remedied if the airplane were constructed of a nonconducting dielectric material such as a plastic or ceramic. If this were done, charges would not be free to move under the influence of the thunderstorm electric field, and induced charges and the consequent intensification of the electric field could not take place.

It appears that this idea is entirely impractical. Everything in the interior of the airplane would have to be nonconducting, and the unacceptable condition would have to be met of no wiring at all. Furthermore, even assuming that the airplane and engines were nonconductors, people inside of it would still be rather good electrical conductors, and they now would be unshielded and experience large electric forces.

Even a completely nonconducting airplane would by no means provide insurance against strikes by lightning, for it could still be hit by chance, and if it were, the results could be serious. We have seen that when lightning strikes a nonconductor the structural damage can be severe. Furthermore, in a nonconducting airplane the fuel supply would be afforded little protection and would possibly explode in the event of a strike.

The nonconducting airplane idea is completely unrealistic, for it gives rise to far more problems than it solves. A reasonable approach to the airplane lightning problem requires that we accept the limitations of the conducting airplane and consider what might be done to reduce its vulnerability to lightning.

### LOWER THRESHOLD FOR POINT DISCHARGE

The concentration of the lines of force and therefore the electric field at the surface of an airplane depend on the radius of curvature. It is therefore possible to promote the formation of point discharge by placing sharply pointed objects on the extremities of the airplane. In this way one can reduce the density of the charge, induced or otherwise, that is on the airplane. The so-called static dischargers or wicks attached to the wings and tail surfaces of airplanes to regulate the flow of corona and reduce radio interference have this effect (Hucke 1939).

It is not clear what effect static dischargers or similar structures that prevent point discharge would have on the likelihood that an airplane would be struck by lightning, for they would have two opposing effects. Although they might tend to inhibit the initiation of a lightning stroke at the airplane



surface by reducing the strength of the electric field, at the same time they would increase the release of space charge that might attract an advancing stepped leader. Whatever the effect of points or dischargers, it is clear that they do not afford adequate protection from lightning, for they themselves often receive the discharge.

#### INCREASE THRESHOLD FOR POINT DISCHARGE

The electric field intensity and the formation of point discharge can, to a certain extent, be reduced by increasing the radius of curvature of the surface on the extremities of the airplane. This might be expected to have two opposing effects on the probability of lightning. Although such a procedure would reduce the electric field and therefore might be expected to decrease the initiation of a leader, laboratory experiments show that surfaces having large radii of curvature appear to favor spark formation.

Whatever the effect of increasing the radius of curvature, it is clear that this procedure is not an effective lightning prevention measure, for strikes are common to surfaces having a large radius of curvature, such as the nose and wing tanks.

This problem of whether the likelihood of a lightning strike to an airplane is influenced by the radius of curvature of its surface is a modern-day version of the old and still unanswered problem of whether or not lightning rods increase the likelihood of lightning. If there is an effect, it is not large enough to be easily recognized, for lightning strikes both pointed and rounded surfaces frequently, both on airplanes and on grounded structures. All available evidence indicates that there is little hope of reducing the chances of an aircraft's being struck by lightning by modifying the shape of the structure or by the attachment of pointed electrodes.

#### CONTROL OF THE NET CHARGE OF THE AIRPLANE

Waddel et al. (1946) and others have developed equipment that can increase or decrease the electric charge on the airplane by the release of charged water drops or ions. Apparatus can be arranged to maintain the airplane in an electrically neutral condition or at some desired level and polarity of net charge. The magnitude of the charge that can be maintained by such an apparatus is limited by point discharge which, as we have discussed, will cause the charge to leak off rapidly from sharp extremities when the electric field becomes large.

There are reasons for believing that the net electric charge on the airplane would have an effect on the path taken by lightning, and Malan (1963) has stated that "as static charge is liable to attract lightning it is advantageous to get rid of the charge by some means." This might be done by the use of sharp points to bleed off the charge or by the use of apparatus such as we have just mentioned.

If a lightning leader stroke advancing toward the airplane were to be carrying negative charge, conceivably one might repel it by charging the airplane negatively. Conversely, if the strike were carrying positive charge, one might repel it with positive charge on the airplane.

While charge manipulation of the airplane in principle provides a method for minimizing the probability of a lightning stroke to the airplane, it appears doubtful that the effect would be significant. The net electric charge that can be carried by the airplane is limited by point discharge to such small values that even the maximum charge possible would produce only very short range effects in comparison to the far larger charges in the cloud. Therefore, neutralizing this charge would have insignificant long range effects. Close to the airplane, it might be possible to neutralize the effects of the autogenous charge, but it would not be possible to neutralize the effects of the exogenous charge. The effects of this latter charge would probably be large enough either to initiate leader strokes and streamers or to attract the leader toward the airplane. The electrical effects of an electrically neutral airplane in the thunderstorm may be somewhat analogous to the electrical effects produced by tall towers and their electrical image in the earth. Tall structures, it is well known, can "attract" lightning and, as we have mentioned, can in some cases initiate a discharge.

Charging the airplane so as to repel lightning does not appear to be a hopeful method. Again, the exogenous charges that are developed probably far exceed any charge that might be given the airplane, so that the applied charge would have at best only a second-order effect.

A further difficulty with this method is that it would be almost impossible to detect the polarity of the advancing lightning charge and to charge the airplane appropriately in the short time available.

#### CONTROL OF AIRPLANE POTENTIAL

In order that a lightning discharge can jump to an airplane it is necessary that there be an electrical potential difference between the cloud and airplane sufficiently large that the spark will form. In principle, if it were possible to make the potential of the airplane equal to the potential of the advancing lightning there would be no electrical driving force, and the spark would avoid the airplane. Unfortunately, this does not appear to be a feasible solution. The potential of the airplane is a function not only of the electric charge on the airplane but also of the electric charge in the thunderstorm. Adopting the convention that the earth is at zero potential, the potential of the airplane as the result of the charge in the storm may well be of the order of hundreds of millions of volts. The rate at which current flows from an airplane by point discharge increases as the square of its potential (Gunn et al. 1946), so it is doubtful if one could alter its potential artificially by more than a few megavolts at most. Even if it were possible to know what potential one should make the plane in order to match the potential of lightning, one would in general have to place charges on the plane that would alter its potential by hundreds of megavolts in a few milliseconds - a clearly impracticable solution.



It will be recognized that protection of the airplane by potential manipulation is entirely equivalent to protection of the airplane by charge manipulation. These two discussions therefore amount to looking at the same problem in two slightly different ways that point to the same conclusion: that one cannot prevent lightning discharges to the airplane by manipulating the charge that it carries.

#### ELECTRICALLY SEGMENTED AIRPLANE

Thus far we have considered two situations, the electrically conducting metal airplane and the highly impractical nonconducting airplane. It is worth giving some consideration, too, to airplane design in which the fuselage is made up of conducting metallic portions that are electrically separated from each other by a nonconductor. With such an arrangement it would be possible to maintain appreciable potential differences between various portions of the fuselage and thus perhaps to exercise some effect on the lightning.

It would be possible to reduce considerably the induced charges on the wing tips by electrically insulating them from the rest of the airplane. If this were done, charge would no longer be free to flow along the wing, and the field concentration effect at the end of the wing would considerably reduced. While the field would be reduced here, it would be intensified at the extremity of the inner conducting section.

This type of construction would, it appears, be capable of achieving some reduction in the field perturbation caused by the airplane, so long as no charge could flow across the insulating sections.

There is very considerable doubt whether it would be possible to provide insulation that would be adequate when the airplane was in a strong electric field. In a thunderstorm potential gradient of  $3000 \text{ v cm}^{-1}$  the wing of a modern jet airplane spans a potential difference of the order of  $10^7$  volts. It is doubtful if it would be possible to maintain the integrity of necessarily exposed insulators capable of withstanding such potential differences, particularly in the presence of rain and cloud droplets.

Even if this were possible, this sort of arrangement would probably not reduce the field perturbation sufficiently to prevent lightning. When lightning did occur, electric breakdown of the insulation would certainly be a possibility and would present a serious additional hazard. This system for reducing lightning appears to provide only a slight reduction in the possibility of lightning at a prohibitively high price of new hazards and added difficulty of construction.

#### SURFACE COVER OF INSULATING MATERIAL

It would be possible to cause a considerable modification of the electrical characteristics of the airplane surface by coating it with an insulating material such as a paint or plastic. If this were to be done, the electric charge on the airplane would no longer reside on the outside surface but on the metal surface beneath it.



As a result of the nonconducting film, the charge on the metallic surface would not be free to escape as point discharge, so that intense electrical stresses could build up in the film and in the air. In the event that the film was capable of withstanding the strong field, the air would break down and a screening layer of charge having a polarity opposite to that on the metal would form on the outside of the insulating film and reduce the electric field of the airplane. This reduction of the field might conceivably cause a reduction in the likelihood of a lightning strike.

Again, while this method would appear to have some virtues, it has serious difficulties. It appears doubtful that any insulating material would be capable of withstanding the electrical field that would develop in the insulation. If the insulation could withstand the field, the accumulation of charge on the surface would be a hazard, for it could discharge in the form of sparks when the airplane was on the ground and initiate a fire, shock personnel, or damage the airplane.

When one considers that there are often very rapid field changes immediately prior to the lightning, it appears problematical whether the charge distribution on the insulation could change rapidly enough to give any protection. This technique appears to be ruled out as a practical approach to the problem by its many disadvantages and by a considerable uncertainty that it would work.

#### CONTROL OF ELECTRICAL CONDUCTIVITY OF AIR SURROUNDING AIRPLANE

A possible method for the protection of an airplane from lightning strokes would be to surround it by highly conducting ionized air. This would provide a gaseous conductive shield.

When it is considered what enormous quantities of air flowing over the airplane would have to be ionized, the energy and apparatus requirements for this technique appear to be impractical and prohibitively expensive.

#### CONTROL OF DIELECTRIC PROPERTIES OF AIR SURROUNDING AIRPLANE

It is known that certain gases, particularly the halogens and compounds such as  $\text{CCl}_4$ ,  $\text{CCl}_2\text{F}_2$ ,  $\text{CCl}_3\text{F}$  and  $\text{C}_2\text{Cl}_2\text{F}_4$  (Cobine 1941) have a high affinity for free electrons and raise the electric field intensities required to produce an electrical discharge. It is conceivable that it might be possible to reduce the probability of an airplane's receiving a lightning discharge by releasing these gases from the extremities of the fuselage and wings. Because of the speed of the airplane it would be necessary to release very large amounts of gas to produce concentrations having an effect, and it appears that this method of protection would be extremely expensive in terms of the material that would be required. There is considerable doubt if it would provide adequate or even significant protection.

### SCREENING CONVOY OF PROTECTING AIRPLANES

It appears that it may be possible to prevent one airplane from being struck by lightning by protecting it with a screening convoy of other airplanes. If the one airplane is completely surrounded by protective airplanes that are flying much closer to each other than to the airplane they protect, then a lightning discharge might be diverted and pass from one screening airplane to another.

Such an arrangement appears quite impractical, not only because of its great expense but because the danger of collision would be far more serious than the original hazard posed by the lightning.

## CONCLUSIONS

If an airplane is flown in or near to electrified clouds, it may become a part of the conducting path of a lightning discharge as the result of the following possible occurrences:

(1) The airplane may fly into a lightning discharge that by chance occurs just in front of it.

(2) The advancing leader of a developing lightning discharge may by chance pass through the airplane.

(3) The advancing leader of a developing lightning discharge may be attracted to the airplane by the charge on the airplane or by the charge released by the airplane.

(4) The airplane may produce an ionization process such as leaders or streamers that will initiate a lightning discharge or make contact with an existing discharge.

On the basis of our present knowledge it appears that other than the complete avoidance of electrified clouds no feasible method exists for preventing these processes. There is not sufficient time to steer clear of the lightning in occurrence (1), and no techniques appear to be feasible either to warn of the imminent occurrence of lightning or to forestall its approach or initiation.

Since it is not feasible to prevent lightning discharges, the primary approach to minimizing the hazards posed by lightning must be to assume that lightning will strike and to design the airplane to withstand it.

The energy of lightning discharges is subject to wide variation. Many of them leave no mark at all on the airplane, some make small pits on the metal skin, and only a small percentage are sufficiently energetic to produce holes or to cause structural damage.

As yet we do not know enough about the conditions inside of thunderclouds to predict when or where lightning will form that is sufficiently energetic to produce damage. With a better knowledge of electrical storms, it may be possible to recognize and to avoid those rather rare conditions that produce dangerous lightning.



## RECOMMENDATIONS

Establishment of airplane designs and operating procedures that afford the maximum protection against lightning will require a much better understanding of this phenomenon than is presently available. It is recommended that laboratory and field investigations be carried out to improve knowledge in this area. Examples of some of presently unanswered problems that should be pursued are the following:

- (1) To what extent are lightning discharges triggered by the airplane?
- (2) Under what conditions does the lightning remain embedded in the atmosphere so that the airplane moves relative to the ionized channel, and under what conditions is the lightning channel carried along with the moving airplane so that successive strokes and the continuing current enter the airplane at about the same point?
- (3) Under what conditions can the airplane become detached from a lightning discharge?
- (4) What are the instantaneous values of the electric field about the airplane when it is struck by lightning?
- (5) What is the range of the quantities of electric charge that are transferred when an airplane is struck by lightning?
- (6) What are the current-time relationships for lightning discharges to airplanes, and how are they related to the damage they produce?
- (7) What is the probability that a lightning discharge to an airplane will lie in any specified range of energies?
- (8) What are the meteorological conditions that lead to the production of lightning discharges of sufficient energy to damage airplanes?

## BIBLIOGRAPHY

- Aiya, S.V.C. and B.S. Sonder, 1964: Lightning flashes on warm quiet days of spring in Bangalore. Proc. IEEE, Vol. 52, No. 9, p 1062.
- Ashmore, S.E., 1950: Unusual lightning. Weather, Vol. 5, No. 9, p 331.
- Atlas, D., 1963: Radar analysis of severe storms, Meteor. Monogr., 5, Boston, Amer. Meteor. Soc., p 210.
- Baskin, D., 1952: Lightning without clouds. Bull. Amer. Meteor. Soc., Vol. 33, No. 8, p 348.
- Boys, C.V., 1926: Progressive lightning. Nature, 118, pp 749-750.
- \_\_\_\_\_, 1927: Progressive lightning. Nature, 119, p 279.
- Brook, M. and B. Vonnegut, 1960: Visual confirmation of the junction process in lightning discharges. J. Geophys. Res., Vol. 65, No. 4, pp 1302-1303.
- \_\_\_\_\_, G. Armstrong, R.P.H. Winder, B. Vonnegut and C.B. Moore, 1961: Artificial initiation of lightning discharges. J. Geophys. Res., Vol. 66, No. 11, pp 3967-3969.
- Cobine, J. D., 1941: Gaseous Conductors. Theory and Engineering Applications, Dover Publications Inc., New York, p 183, 606 pages.
- Dewan, E.M., 1964a: Physical Sciences Research Paper, No. 67. Attempted Explanations of Ball Lightning, Upper Atmosphere Physics Laboratory Project 8627, AFCRL-64-927.
- \_\_\_\_\_, 1964b: Eyewitness accounts of Kugelblitz, CRD-125, Microwave Physics Laboratory, AFCRL.
- Doyle, A., D. R. Moffett, B. Vonnegut, 1964: Behavior of evaporating electrically charged droplets. J. Colloid Sci., Vol. 19, No. 2, pp 136-143.
- Faucher, G. A. and H. O. Curtis, 1958: Hazards of lightning discharge to aircraft. Air Force Surveys in Geophysics, No. 103, AFCRC-TN-58-424, 18 p incl. illus.
- Fitzgerald, D. R., 1964: Measuring techniques in clouds. To be published in Proceedings of the Third Conference on Atmospheric Electricity, Montreux, Switzerland, May 1963, Elsevier Press, Amsterdam.
- Gifford, T. H. F., 1950: Aircraft struck by lightning. The Meteorol. Mag., April, No. 934, Vol. 79, pp 121-122.

- Gisborne, H. F., 1928: Lightning from clear sky. Monthly Weather Review, Vol. 56, No. 3, p 108.
- Gish, O. H. and G. R. Wait, 1950: Thunderstorms and the earth's general electrification. J. Geophys. Res., Vol. 55, p 473.
- Gunn, R., W. C. Hall and G. D. Kinzer, 1946: The precipitation-static interference problem and methods for its investigation. Proceedings of the IRE and Waves and Electrons, Vol. 34, No. 4, p 156.
- \_\_\_\_\_ and J. P. Parker, 1946: The high voltage characteristics of aircraft in flight. Proceedings of the IRE and Waves and Electrons, Vol. 34, No. 4, pp 241-247.
- \_\_\_\_\_, 1948: Electric field intensity inside of natural clouds. J. Appl. Phys., 19, pp 481-484.
- \_\_\_\_\_, 1955: Discussion on page 242, Proceedings on the Conference on Atmospheric Electricity, Geophysical Research Paper No. 42, AFCRCTR-55-222, Geophys. Res. Directorate.
- Hagenguth, J. H., 1951: The lightning discharge. Compendium of Meteorology, Am. Meteorol. Soc., Boston, pp 136-143.
- Hurst, G. W., 1956: Aircraft struck by lightning. The Meteorol. Mag., No. 1010, Vol. 85, pp 248-249.
- Kinzer, G. D. and J. W. McGee, 1946: Investigations of methods for reducing precipitation-static radio interference. Proceedings of the IRE and Waves and Electrons, Vol. 34, No. 5.
- Ligda, M. G. H., 1956: The radar observation of lightning. J. Atmos. Terrest. Physics, 9, pp 329-346.
- McCaughan, Z. A., 1926: A lightning stroke far from the thunderstorm cloud. Monthly Weather Review, Vol. 54, No. 8, p 344.
- McEachron, K. B., 1939: Lightning to the Empire State Building I, J. Franklin Inst., 227, pp 149-217.
- \_\_\_\_\_, 1941: Lightning to the Empire State Building II, Trans. Am. Inst. Elec. Engrs., 60, pp 885-890.
- Malan, D. J. and V. F. J. Schonland, 1947: Progressive lightning VII. Proc. Roy. Soc., A191, pp 458-503.
- \_\_\_\_\_ and \_\_\_\_\_, 1951: The distribution of electricity in thunderclouds. Proc. Roy. Soc., A209, pp 158-177.
- \_\_\_\_\_, 1952: Les décharges dans l'air et la charge intérieure positive d'un nuage orageux. Ann. Geophys., Paris, 8, pp 385-401.
- \_\_\_\_\_, 1963: Physics of Lightning. The English Univ. Press, Ltd., London 175p.



- Mason, D., 1964: Lightning strikes on aircraft - II. Weather, Vol. XIX, No. 8, p 254.
- Moore, C. B., B. Vonnegut, B. A. Stein and H. J. Survilas, 1960: Observations of electrification and lightning in warm clouds. J. Geophys. Res., Vol. 65, No. 7, pp 1907-1910.
- Myers, F., 1931: Lightning from a clear sky. Monthly Weather Review, Vol. 59, No. 1, p 39.
- Newman, M. M., 1953: Aircraft and lightning. Thunderstorm Electricity. Edited by H. R. Byers, Univ. of Chicago Press, pp 328-335.
- \_\_\_\_\_, J. D. Robb and E. H. Yonkers, 1962: Aircraft protection from thunderstorm electromagnetic effects. Conference Paper No. CP62-1133, American Institute Electrical Engineers, 43 pages.
- \_\_\_\_\_, 1963: Aircraft protection from thunderstorm electromagnetic effects. Final Report, No. ASD-TDR-62-438, Part V, AF Avionics Lab, Electronic Warfare Div., Wright-Patterson Air Force Base, Ohio, 110 pages.
- \_\_\_\_\_, J. D. Robb and J. R. Stahmann, 1964: Lightning protection measures for aircraft fuel systems. Technical Report ADS-17, Federal Aviation Agency, Washington, D. C.
- \_\_\_\_\_, 1964: The use of triggered lightning to study the discharge and chemical processes in the channel. Proceedings of the Third Conference on Atmospheric Electricity, Montreux, Switzerland, May 1963, Elsevier Press, Amsterdam.
- Pietrowski, E. L., 1960: An observation of lightning in warm clouds. J. Meteorol., 17, 5, pp 562-563.
- Reynolds, S. E., 1954: Compendium of thunderstorm electricity. U. S. Signal Corps. Report (Socorro, New Mexico).
- \_\_\_\_\_, and H. W. Neill, 1955: The distribution and discharge of thunderstorm charge centers. J. Meteorol., Vol. 12, No. 1, p 1-12.
- Schonland, B. F. J., 1928: The interchange of electricity between thunderclouds and the earth. Proc. Roy. Soc., A118, pp 252-262.
- \_\_\_\_\_, 1953: Atmospheric Electricity. Methuen & Co. Ltd, London, p 63.
- \_\_\_\_\_, 1956: The Lightning Discharge Handbuch der Physik - Band XXII Gasentladungen II, Springer-Verlag, Berlin, Gottingen, Heidelberg.
- Shackford, C. R., 1960: Radar indications of a precipitation-lightning relationship in New England thunderstorm. J. Meteorol., 17, 15-19.
- Simpson, G. C. and G. D. Robinson, 1940: The distribution of electricity in thunderclouds. II Proc. Roy. Soc., A177, pp 281-329.

- Stergis, C. G., G. C. Rein and T. Kangas, 1957: Electric field measurements above thunderstorms. J. Atmos. and Terrest. Phys., Vol. 11, Pergamon Press Ltd., London, pp 83-90.
- Stimmel, R. G., E. H. Rogers, F. E. Waterfall and R. Gunn, 1946: Proceedings of IRE and Waves and Electrons, Vol. 34, No. 4, p 176.
- Vonnegut, B. and C. B. Moore, 1959: Giant electric storms. Recent Advances in Atmospheric Electricity, Pergamon Press, pp 399-411.
- \_\_\_\_\_, 1963: Some facts and speculations concerning the origin and rate of thunderstorm electricity. Meteorol. Monog., Vol. 5, No. 27, Am. Meteorol. Soc., Boston, pp 224-241.
- Waddel, R. C., R. C. Drutowski, W. N. Blatt, 1946: Aircraft instrumentation for precipitation static research. Proc. of IRE and Waves and Electrons, Vol. 34, No. 4.
- Williams, D. P. and M. Brook, 1963: Magnetic measurements of thunderstorm currents. Continuing Currents in Lightning. J. Geophys. Res., Vol. 68, No. 10, pp 3243-3247.
- Wilson, C. T. R., 1920: Investigations on lightning discharges and on the electric field of thunderstorms. Trans. Roy. Soc., A221, 73, p 100.
- \_\_\_\_\_, 1956: A theory of thundercloud electricity. Proc. Roy. Soc., A236, pp 297-317.
- Wood, C. A., 1951: Unusual lightning. Weather, Vol. 6, No. 2, p 64.
- Workman, E. J. and S. E. Reynolds, 1953: Structure and electrification. Thunderstorm Electricity, pp 139-149.
- Wormell, T. W., 1930: Vertical electric currents below thunderstorms and showers. Proc. Roy. Soc., A127, pp 567-590.
- \_\_\_\_\_, 1953: Atmospheric electricity; some recent trends and problems. Quart. J. Roy. Meteorol. Soc., Vol. 79, No. 339, pp 3-38.
- Wright, J. B., 1950: A thunderstorm in the tropics. Weather, Vol. 5, No. 6, p 230.
- Young, G. A., 1962: A lightning strike of an underwater explosion plume, Task RE01-ZA732/212 9/-WF008-21-003, Naval Ordnance Laboratory Technical Report 61-43.