# MAGNETOHYDRODYNAMIC PHENOMENA

# IN THUNDERSTORMS

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## PREFACE

The identification and tracking of tornado spawning thunderstorms has been the subject of considerable research for the past decade. This research has resulted in significant progress in determining the identifying electromagnetic signals generated by such storms, but has not produced an absolutely unique identification characteristic.

This thesis is devoted to the presentation of an original hypothesis on the generating mechanism of a tornado, and includes the collection and analysis of electromagnetic radiations of lightning discharges as correlated to specific discharge types. Although this data and analysis does tend to support the author's hypothesis, it also provides useful information for all other present research.

The data for this investigation was obtained with the use of available equipment at the Tornado Laboratory of Oklahoma State University. My gratitude goes to the men who designed this equipment and to the technicians and engineers who maintain it and process the data obtained thereon. My thanks also, to my typist, Mrs. Barbara Adams, for her painstaking efforts in preparing this thesis for publication.

I want to express my special appreciation to Mr. George Lucky, who spent many hours helping me to operate the equipment in collecting data, for hearing me out on my many and varied theories, and for offering, in turn, considerable encouragement, suggestions, and guidance on these theories.

My particular appreciation goes to Dr. H. L. Jones, for his open-mindedness in allowing me to conduct research on such a controversial and hypothetical subject, and for his encouragement and advice throughout my investigation.

To Dr. Bernard Vonnegut, of Arthur D. Little, Inc., to Mr. Donald J. Ritchie, Supervisory Mathematician of the Advanced Research Group of Bendix Aviation Corporation, and to Mr. G. B. Bathurst, of Cirencester, England; a special note of thanks for their encouragement on my hypothesis and for the references and research material they contributed in support of my efforts.

Loving thanks to my wife, Vivian, whose constant faith in me and continued encouragement even in moments of academic despair, were instrumental in helping me to finish this dissertation in the time available.

Finally, lest I ever forget that the wonders of the Universe and the fascinating revelations of the study of physical science, are, in reality, only natural in the orderliness and perfection of the divine scheme of life--I want to publicly express my thanks to God for his divine guidance, and for granting me even the slightest bit of new knowledge from the vast store of infinite wisdom as yet undisclosed to mankind.

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# CHAPTER I

## INTRODUCTION

The spectacular, but very destructive weather phenomenon known as a tornado has been under study or consideration by mankind for many centuries. Two distinct and separate schools of thought on tornadic mechanisms have evolved from this study. The first of these attributes the tornado to air mass movements, shear effect, rapid vertical air currents, or other associated moving air phenomena. One such advocate is Dr. H. L. Jones, (1) director of the Tornado Research Project of Oklahoma State University, the originator of the "tornado oscillator" concept, and a highly regarded leader of research on sferics--atmospheric electromagnetic signals generated by both thunderstorms and tornadoes. Jones and the great majority of other weather phenomena investigators attribute the frequently reported displays of electrical phenomena in some tornadoes, to the tornado itself, or to the thunderstorm which has produced it.

On the other hand, there has always existed a small group of scientists who have supported the possibility that tornadoes are the result, rather than the cause of, these associated displays of intense electrical activity. Vonnegut (2) appears to be the leader of this present day minority, and presents his beliefs explicitly and thoroughly in the referenced literature.

During the past fifteen years, the study of sferics has done much to uncover some of the mysteries of tornado spawning thunderstorms and has even brought man to the verge of being able to positively identify and track potential and existing tornadoes--an obvious boon to the unfortunate masses who live in areas of seasonal tornadic activity. Unfortunately, there are still many missing areas of specific knowledge on unique tornado characteristics. The ultimate attainment of this knowledge may very well depend upon the discovery and proof of the exact mechanism by which a tornado is developed.

This dissertation presents the theoretical development of such a mechanism, following the Vonnegut school of thought and based on certain accounts of experimental observations in an area of research relatively foreign to the study of atmospheric electricity.

However, before proceeding further, it would be well to first present an explanation of the rather unusual title of this thesis and the specific investigatory efforts taken to justify it.

The classification of certain thunderstorm phenomena as being in the relatively new field of magnetohydrodynamic phenomena (to be abbreviated in the remainder of this report as MHD phenomena), presents a new basis for some extremely fascinating theoretical explanations of such phenomena. However, in view of the hypothetical nature of such a study, it was felt necessary to choose a comparatively basic point of departure upon which to collect and analyze data, in an attempt to either provide a reasonable and valid scientific basis for further MHD investigation or, failing to do this, to at least contribute some useful data to the ever increasing mass of information presently being compiled on atmospheric electricity.

## Magnetohydrodynamics

Magnetohydrodynamics has been defined by Landshoff (3) as "the study of the interaction between magnetic fields and moving, electrically conducting fluids"--in the case of this report, ionized gas mixtures known in the field of science as plasma.

Cobine (4) describes plasma as an ionized region existing in many gas discharges, in which the concentrations of positive and negative ions are approximately equal and are relatively high. Such regions are highly conducting, with the negative carriers being electrons and the positive carriers--positive ions. The positive ions, electrons, and neutral gas particles of the plasma, may or may not be in thermal equilibrium. Since a plasma is normally established by an applied electric field, the temperature of the positive ions is usually greater than the gas temperature, and the electron temperatures may be very high indeed. When an electric field is applied to a plasma, the drift current density (that current in the direction of the applied field) is usually much smaller than the random current density of ions and electrons; thus the applied field does not necessarily produce a departure from the maxwellian distribution (velocity distribution) of these particles, although it does increase the ion and electron temperatures. This increase in the temperatures of the charged particles will be greatest for the electrons, which, because of their comparatively smaller mass, will give up very little energy to neutral particles with which they collide. The positive ions, on the other hand, will increase the gas temperature, since the masses of the colliding ions and neutral particles are comparable.

Although a plasma is essentially neutral when a large volume is considered, there must be rather high fields existing at points throughout the volume depending on the instantaneous grouping of charged particles around these points. Electrons may gain considerable amounts of energy when passing through such point fields. Since the ionization of a plasma is maintained primarily by electron collision and some photoionization, this increase in electron energy would tend to support the possibility of the self-sustained existence of a plasma in a changing electric field. This point is particularly important to certain MHD phenomena discussed in the next chapter.

Another aspect of plasma, which may prove very significant in future research on the generation process of sferics, is that of plasma oscillations, a subject covered quite thoroughly in the literature. (4, 5, 6, and 7). Two types of longitudinal oscillations may be considered possible in a plasma: an oscillation of electrons about a mean fixed position and at a frequency which represents the lower limit for the propagation of longitudinal waves in the plasma: and an oscillation of positive ions producing waves which might be called "electric" sound waves because of their similarity to ordinary sound waves. (4).

Although the ideal case of the propagation of plasma waves by electron oscillations can theoretically transmit no energy, Cobine (4) points out that such oscillations may transmit energy if the oscillating electrons are moving through the gas as a group, as they can move in an electric discharge.

At this point, it may appear to the student of atmospheric electricity that the only thing original about the MHD concept is the coining of a new word, in view of the many ion-electron theories published on cloud electrification, high pressure arcs, and ball lightning phenomena. (8, 4, and 9). However, this is definitely not the case, since none of these investigations has included a consideration of the MHD essential of magnetic field interaction on ionized air. A possible exception to this is

Ritchie, (10) in attributing the luminous aspects of the common lightning stroke to a plasma "pinch." This particular phenomenon is developed in the works of Rosenbluth (11) and has provided a sounder and more acceptable explanation of gaseous discharge arcs than was previously and erroneously held.

The MHD phenomena hypothesized upon in this report are those which could occur as the result of high pressure arcs (atmospheric lightning strokes) in conjunction with the magnetic field of the earth and/or other induced magnetic fields--this interaction representing the significant difference between the MHD approach and the other tornado mechanism concepts which have preceded it.

In any event, after consideration of the remainder of this dissertation, it should become obvious that MHD phenomena certainly must occur in severe electric storms to some degree--their effects notwithstanding.

The essential ingredients and conditions for MHD phenomena, in addition to certain thought provoking facets of associated research, are presented in more detail in Chapter II.

## Basis for Investigation

Since the electric and electromagnetic manifestations of tornadoes is the basic premise on which the Vonnegut approach is developed, a specific area of research was chosen which might possibly lead to some observable correlations of electromagnetic data with the conditions necessary for the occurrence of MHD phenomena. Inasmuch as sferics are the electromagnetic signals generated by lightning discharges, an investigation of the mechanism by which particular frequency bands of these sferics are generated, could establish a basis for understanding the physical changes of that mechanism which result in a type of sferic unique to either tornado spawning thunderstorms or to tornadoes themselves.

Sferics research by Jones (12) for the past twelve years has revealed that such signals range in significant frequency content from 10 kc to 150 kc, the 10 kc and 150 kc bands representing the predominant energy levels and occurring in various combinations with one another. The most significant and important development of this research was that of Jones and Hess (13) in 1952, when a tornado, both visually and electronically observed, indicated a propensity for generating sferics predominantly in the 150 kc band, and at a rate which increased noticeably prior to, and during, the tornado. This represented the first important unique characteristic of a tornado for use in detection and tracking purposes. However, subsequent observations by Jones (12) and his staff have also revealed that these characteristics are not absolutely unique, in that the increase in sferics count sometimes occurs from 30 to 90 minutes prior to an observed tornado, while at other times occurring coincidentally with the actual funnel. Excellent examples of this latter case were two tornadoes of May 25, 1955, which did extensive damage to the towns of Blackwell, Oklahoma, and Udall, Kansas, after having been tracked and visually observed by Jones (1) for approximately 150 miles. These tornadoes were among the first in which specific warning was possible to towns lying in the path of destruction--a warning instrumental in saving many lives.

The lack of an absolutely unique characteristic of a mature tornado still exists and it is fervently hoped that an introduction of the MHD line of research may result in the eventual discovery of such an identifying label.

## CHAPTER II

## DEVELOPMENT OF HYPOTHESIS

In view of the fact that the major significance of this dissertation is in the application of MHD theory to the study of atmospheric electricity, a statement of this new hypothesis will now be presented.

It is theoretically possible that a tornado may be the result of atmospheric MHD phenomena in the form of plasma entities, created by rapidly recurring high pressure arcs through relatively limited areas of ionized gas mixtures in thunderstorm cells; and then maintained, or even increased in size, by energy drawn from the existing high potential of these cells. These entities then cause the rapid movement of air in a vertical or near vertical columnar space, resulting in the familiar tornado funnel. The rapid vertical air movement may be the result of either direct convection heating or a dissociation process around, or through the plasma entity.

It should be immediately obvious that little hope existed for any spectacularly conclusive observations of this phenomenon from the outset of this investigation, inasmuch as these observations were necessarily external to, and dependent upon, the natural occurrence of thunderstorms or tornadoes.

The hypothesis itself is based on research reading and considerable speculation in three particular areas of current scientific endeavor. These areas will be discussed in four separate subsections of this chapter--the first being a brief resume of the previously mentioned eye witness reports on peculiar tornadic electrical phenomena. The second section is an account of certain laboratory experiments involving plasma entities and some of their unusual and fascinating characteristics as observed by W. H. Bostick (14, 15, 16) and his staff, of the University of California. The third section covers two important and fundamental aspects of MHD theory as applied to the attempted attainment of controlled thermonuclear reaction by the Atomic Energy Commission. The fourth section is a very brief review of the conditions existing in thunderstorms, particularly those which coincide with the conditions necessary for MHD phenomena to occur.

## Tornadic Electrical Activity

The vivid electrical displays sometimes associated with tornadoes have even been recorded as early as 50 B.C. in the works of Lucretius, and later by Francis Bacon in about 1600. (2). Much more valid and interesting reports have been assembled in modern times by Flora (17) and by Vonnegut. (18). Passages from the works of each of these authors will be included herein.

Generally these reports have contained accounts of variously colored intense luminescence in and around the tornado spawning clouds and the funnels themselves. These colors have ranged from pale bluish-greens to bright orange; in shape from dancing tongues of flame and seas of fire to glowing clouds, rays of light, and balls of fire. Accompanying these luminescent characteristics have been reports of various and sundry sounds; such as the roar of approaching trains or jet aircraft, the buzzing of bees or buzzsaws, and the crackling of breaking twigs or dried sticks. A few reports from individuals fortunate enough to live through extremely close encounters, have mentioned peculiar odors likened to sulfur, brimstone or the electric circuit smell of ozone. Humphreys (19) points out that the scorching of air by electrical activity is actually caused by the disruption of oxygen, nitrogen, and water vapor molecules, such that their resultant combinations with whatever else is present, produces new substances such as ammonia and nitrous or nitric acid. All of these have a pungent odor similar to burning sulfur and, in addition, may offer a reasonable explanation for the various colored luminosity mentioned before.

A few of the more interesting reports contained in the referenced material are listed now to provide a basis for weighing their credence or validity.

From Flora (17) we have the following excerpts:

Destruction starts when this cloud dips to the ground with a terrific roar, often described as resembling the noise of a thousand railway trains crossing trestles or the sound of a cannon prolonged for a few minutes. Observers have also mentioned a peculiar whining sound like the buzzing of a million bees, which is usually heard when the cloud is high in the air..

"After talking to dozens of lay witnesses in the Ft. Wayne, Indiana, area concerning the squall line of April 28, 1951 (which included five embryo tornadoes)," he says, "it was evident from the pattern of replies that the lightning that evening was of an unusual character. Many persons described it as being 'very bright sheet lightning, interlaced lightning way up in the clouds and like lacework.' ...."

"The electrical display during the storm was of exceeding brilliancy. It was first observed at 5:00 P.M., an hour before the tornado occurred. This continued with short intermissions until 5:45 P.M. when it became almost continuous and extended more into the west and north. At 6:00 P.M., when the tornado occurred, the whole west and northwest sky was in a continuous blaze of light. Intensely vivid flashes of forked lightning were frequent, being outlined in green, blue, purple, and bright yellow colors against the dull yellow background of the never ceasing sheet lightning."

Persons who lived through the storm to tell the tale said that the air was filled with fumes like sulphurous smoke, the sky had a reddish tinge bordering on purple, and the ground was rocked as if by an earthquake.

Vonnegut and Moore (18) refer to these eyewitness accounts:

Witnesses of the lightning during the passage of the tornado characteristically say that though there was intense lightning before and after the tornado, there was little or none exterior to the funnel during its passage. However, those who have looked right into the funnel describe various phenomena such as continual lightning, a luminous core, a ball, or ring of fire.

... "There was a fiery flash about two miles away just over the tops of trees and houses. This flash had a duration of about 30 seconds and reminded me of a welder's arc; it started similar to striking the arc, sort of vibrated and then deteriorated to a glow and out. I thought lightning had struck a transformer but wondered about the lack of streak lightning dropping from the sky and hitting the object. As I watched, another flash occurred about 1/4 mile to the left of the original. This time the arc was greenish and the reflection lighting up the area was a weird hue reminding me of the reflection in winter when an ice storm settles on trolley wires and gives off blue or green hues when the trolley contacts the wires. For what seemed like a long time, these arcs alternated at the ends of this 1/4 mile strip with occasional smaller ones between the two points. The right arc had an orange yellow color, and the left a greenish-blue, the color being the same each time the arc appeared....

"As I watched, I would see the flash and after it died out there was a noise coming from the direction of the flash which sounded like the rumble of freight cars when the locomotive backs into the first car to couple on, and the coupling noise progresses down the line...."

Mr. Stevens had been out in his car. As he returned to Silverton, hail began to fall so he drove the car under the canopy of a filling station. He tried his radio to see if he could hear a tornado advisory, but he could receive no signals but a squealing and rapid motorboating sound, something like chalk being dragged across a blackboard. He heard a sound like a jet plane and got out of his car to see if there was a tornado. Just then a heavy fall of large diameter hail almost the size of baseballs with big knobby spikes began. This lasted only 15 seconds or so. Looking to the south he saw about five blocks away a round light in the form of a ring he estimates was 40 or 50 feet off the ground and 40 or 50 feet in diameter. Mr. Stevens said that the lightning came up from the ground and corkscrewed around to join the ring and went up into the cloud. This he identified as a tornado. After it passed, the air was very quiet and there was a strong odor like that around electrical equipment.

"A tornado which occurred on the evening of June 9, 1932, near Rock Rapids, Iowa, gave evidence of a closely related type of luminous display according to the report of Mr. George Raveling, U. S. Weather Bureau. From the sides of the boiling, dust-laden cloud, a fiery stream poured out like water through a sieve, breaking into spheres of irregular shape as they descended. No streak lightning of the usual type was observed and no noise attended the fire balls other than the usual roar of the storm."

From Schonland (20) comes the following account of electrical activity above the clouds:

> One remarkable case, reported by M. D. Laurenson from New Zealand in 1936, took the form of a brilliant ball of light at the top of a bank of clouds. This pulsated in size and intensity for over fifteen minutes, in the course of which time it gave out a very bright greenish-white radiance which lit up the whole of the upper surface of the cloud-bank and illuminated the country-side around as if thousands of searchlights were in action.

One of the most valid reports is that of Jones (1) made while conducting specific research on tornadic activity:

> At the same time a peculiar characteristic of the thunderstorm was also noted from visual observations. There was a notable lack of cloud-to-ground strokes. This condition was contrary to expectation because of the unusual activity evidenced by the direction finder for the azimuth of the thunderstorm.
>
> A peculiar phenomenon, however, was observed that subsequently was considered important. Rapidly recurring patches of light were visible on the side of the thunderstorm cloud next to the observer. These patches were circular in form and approximately one-half mile in diameter. They appeared to be coming from discharges inside the cloud.
>
> It must be emphasized that no cloud-to-ground strokes were observed when the storm was only 12 to 15 miles west of the station....

Finally, the following excerpt is presented for the first time from a description of the Blackwell, Oklahoma, tornado of May 25, 1955, as related to Dr. Jones by Mr. V. F. Finley:

> Mr. Finley described the heavy thunderstorm formation above the funnel and noticed the patch of luminescence in the thunderstorm itself. His description of the lightning activity associated with the luminescent patch differs radically in one form from other descriptions. The luminescent patch was located considerably above the space where the funnel entered the cloud and appeared to be throwing out from its center balls of livid orange fire. As these balls of orange fire emerged from the central patch of luminescence each one would explode and dissipate smaller gobs of fire particles. He pointed out that these exploding balls of light were emerging in all directions from the center of activity. The funnel itself was dark in the case of the 1955 tornado.

Mr. Finley remarked that he remembers almost exactly the same lightning manifestation during a tornado at Blackwell that he viewed in 1945. He remembers the same exploding balls of light emerging from a common center, but he has a different description of the funnel. In the case of the funnel of the 1945 tornado the volume of the funnel appeared to be white, white-light, extending from the cloud base clear to the ground.

As the tornado approached Blackwell in 1955 the electric power failed at the glass plant /where he was working that night/ and consequently no artificial lighting system was available. However, as the storm approached the surrounding area was "almost as light as in daytime." Mr. Finley could see the machines inside the glass plant and other objects in the light that came from the tornado cloud. He asserts that he could see all objects very plainly although the color of the light was quite different, being in general of a whiter nature. He observed no cloud-to-ground strokes and heard no thunder. He did however hear the usual tornado roar, something like the roar of a freight train with an accompanying crackling that sounded like the breaking of many brittle hardwood sticks.

It should be emphasized that these accounts do not represent proof of any theory on tornado development. However, they do provide a pattern of specific observations which tend to support the presence of tornadic electrical activity considerably different from the high pressure arc of the lightning discharge normally associated with thunderstorms.

Vonnegut (2) tabulates these observations and others as part of his electrical theory as follows:

1. Intense St. Elmos' fire frequently observed at night from the earth close to the tornado tip.

2. Luminous glow in associated clouds.

3. Odors of ozone and nitrogen oxides similar to that noticed around high-voltage apparatus.

4. Buzzing and hissing noise suggestive of intense electrical discharge.

5. Widespread ringing of telephones.

6. Intense and continuous local radio static.

7. Scorching and withering of vegetation.

8. Drying of the ground and the wood in trees.

9. Electrical damage to telephone and power wiring.

As a final point of emphasis, the accounts of fire balls or ball lightning covered in the literature, provide one of the fundamental observations in support of the theory on plasma entities, since they stand as evidence that self-contained masses of heated, ionized gas are produced by electrical storms and can exist for appreciable periods of time, even when separated from a regenerative environment. (9, 21, 22, 23). At least one author has considered the theory of ball lightning in relation to "flying saucer" reports, a subject beyond the scope or material of this particular report. (24).

## Plasmoids

Up to this point, plasma entities have received considerable mention in this report in that they do represent a fundamental ingredient of the MHD tornado theory. Bostick (14, 15, 16) has done considerable experimental work on such plasma entities, or as he calls them, "plasmoids." A review of some of the high points of that research is now presented.

Bostick (14) defines plasmoids as plasma entities of various shapes having two properties discovered by Gilbert in 1600, viz.;

1. An ionized gas can conduct electricity.

2. This mass of ionized gas is affected by magnetism.

A study of plasmoids was conducted at the University of California Laboratories at Livermore, and at Stevens Institute, New Jersey, using a plasma gun. This gun consisted of two electrodes of titanium, with deuterium atoms absorbed in them. By pulsing a current of from $10^3$ to

$10^4$ amperes through these electrodes, electrons and ions are evaporated in the form of an arc of plasma containing deuterium ions and surrounded by a girdle-like induced magnetic field as shown in Figure 1.a.

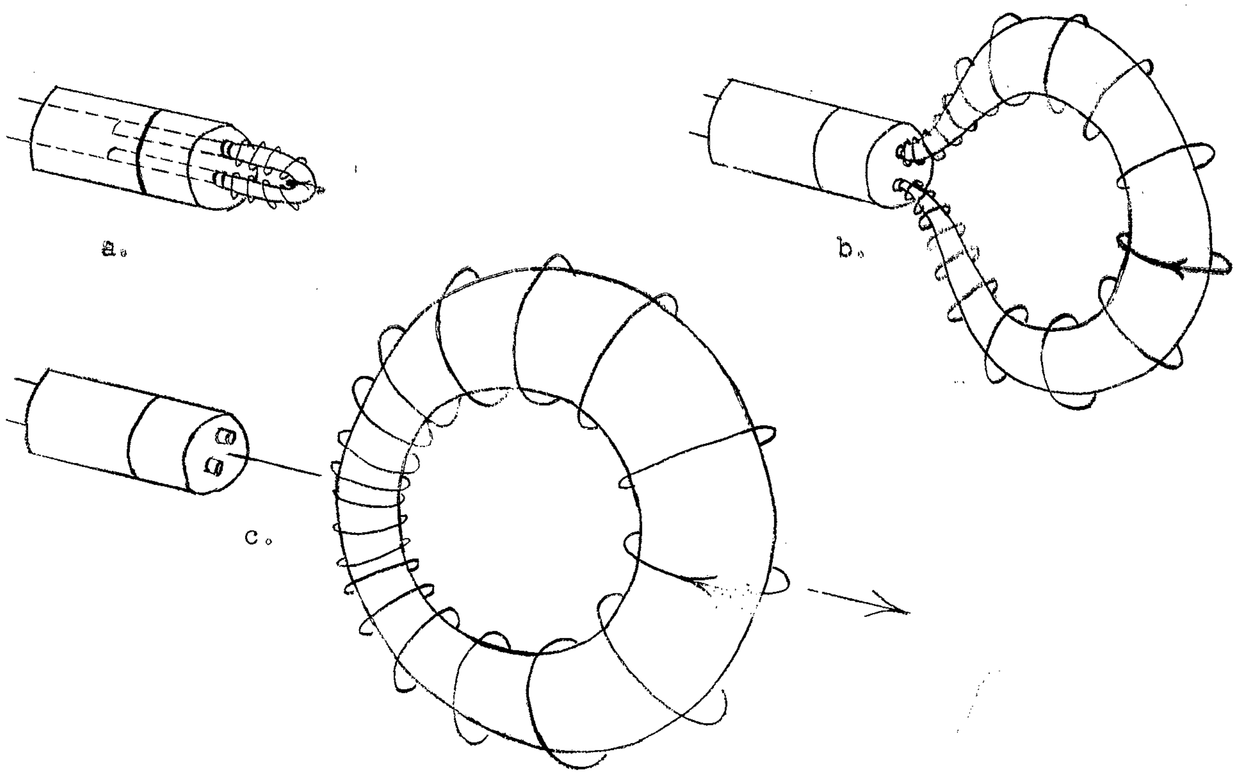


Figure 1. Plasma Gun Firing Plasmoid into a Vacuum. (14).

As a result, this arc bows outward causing the magnetic lines of force on the inner, or concave surface of the arc to become closer together; thus creating a force which drives the plasma blob forward (Figure 1.b.) until it breaks away from the electrodes entirely, assuming a toroidal shape as illustrated in Figure 1.c., and moving at a velocity of approximately 120 miles per second. This assumes a condition of almost complete vacuum with no externally applied magnetic field. This velocity of deuterium ions represents a temperature of 4 million degrees centigrade, and is comparable to the speeds of stars contained in galaxies or of flares from the sun.

A second phase of these experiments was the firing of plasmoids into a vacuum containing an externally applied homogeneous magnetic field. It was originally expected that the plasmoid would encounter considerable difficulty in crossing the magnetic field. However, the plasmoid again crossed the area with extreme ease and with no apparent reduction in velocity. Subsequent measurements with stationary probes along the flight paths of the plasmoids, revealed that the effect of the externally applied magnetic field was to cause the plasmoid to assume the shape of an ever elongating hollow cylinder in the direction of the magnetic lines of force.

A third phase of these experiments was the firing of a plasmoid into a thin gas, (deuterium at 1 micron pressure in this case) and with the magnetic field again applied. This resulted in a partial ionization of the chamber gas, allowing the previously "bottled up" current of the plasmoid to now flow between the gas and the plasmoid, and causing it to lose some of its forward velocity. Figure 2 illustrates a sequence of this process in which the elongated cylinder twists back around itself, transforming the original rolling rotation to a corkscrew type rotation in the forward direction.

Further experiments with multiple firings revealed that two plasmoids tend, in most cases, to repel each other, resulting in elastic collisions similar to ping pong balls rebounding from one another. Even in the collisions in which the individual plasmoids broke apart, the pieces were observed to behave as separate entities with strong powers of <u>self-organization</u>

and preservation.

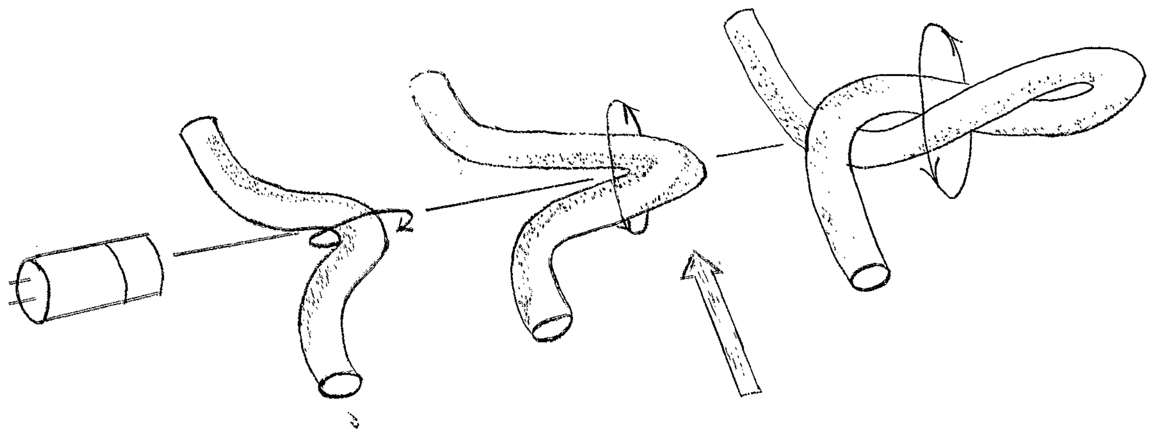

Figure 2. Plasma Gun Firing Plasmoid into Gas Filled Chamber with Externally Applied Magnetic Field. (Heavy Arrow). Bostick. (14).

This latter observation is particularly interesting in view of the aforementioned ball lightning accounts, and the Finley report on "balls of orange fire" in the previous section of this chapter.

Other interesting observations of these experiments revealed that plasmoids fired at each other from four or eight different directions formed whirling pinwheels with spiral-like arms; these pinwheels suspiciously similar to certain celestial formations.

A final observation was that plasmoids are occasionally capable of forming pairs of rings which move away from one another in opposite directions. This would appear to be extremely significant in certain unpublished theories of tornadic development based on horizontally rotating toroids of charged air; one such theory under investigation at the present time by G. B. Bathurst of Cirencester, England.

Detailed explanations of the Bostick experiments are contained in the referenced literature, and offer a convenient starting point in a fascinating area of study.

## Controlled Fusion Research

The previously mentioned attempts by the Atomic Energy Commission to achieve controlled thermonuclear reactions are thoroughly covered by Bishop in his book, Project Sherwood. (25). These attempts have been based on the application of MHD phenomena, certain phases of which are important to the development of the MHD tornado concept. One of these is the M-theory of plasma pinch by Rosenbluth, (11) and the other is described in a treatise by Karr (26) on certain instabilities which have thus far prevented the successful achievement of complete fusion reactions under controlled conditions.

The general principle involved in these controlled fusion attempts is based on the rapid confinement of a plasma, through the use of MHD phenomena, to raise the temperature of the plasma to those ranges necessary for achieving and maintaining the regenerative fusion of nuclei. These required temperatures are in excess of 100 million degrees K.

The essential ingredients of this process are the nuclei of certain elements at the low end of the periodic table; such as hydrogen, deuterium, tritium, and helium. The essential condition for this reaction is that sufficient energy be imparted to the nuclei of these gases to cause them to fuse together, with an ultimate release of considerable kinetic and radiated energy.

The satisfaction of this latter requirement is accomplished by the use of the plasma pinch concept now presented. (11). Due to the high conductivity of plasma, the sudden application of an axial electric voltage produces a thin sheath of electric current on the outside surface of the plasma. This current, in building up, produces an encircling magnetic wall which contracts rapidly toward the center axis, driving electrons and ions radially inward ahead of it. As this advancing magnetic shock wave smashes against these particles, it imparts considerable kinetic energy to them; thus creating the condition of having rapidly moving particles increasing in speed, in an ever decreasing volume. This is another way of saying that the temperature of the plasma has increased. This process is illustrated in Figure 3 in a "before and after" depiction which shows the resulting thin, hot filament of pinched plasma at the completion of the first pulsed reaction. Needless to say, this explanation is exaggeratedly simple and is primarily included here to illustrate the pinch concept of lightning stroke luminosity.

However, before leaving this subject, an important limitation or characteristic of the pinch phenomena provides further supporting evidence to the theory of ball lightning and to a possible explanation of the lifting or twisting motion of a tornado funnel. This is a phenomenon called kink instability. (26).

Figure 4.a. again depicts a fully developed pinch filament, but with a small kink developed as a result of unequal current distribution around the pinch. It can be observed that the lines of induced magnetic force are closest together on the concave side of the kink, (similar to Bostick's plasma gun projectile) causing the irregularity to become

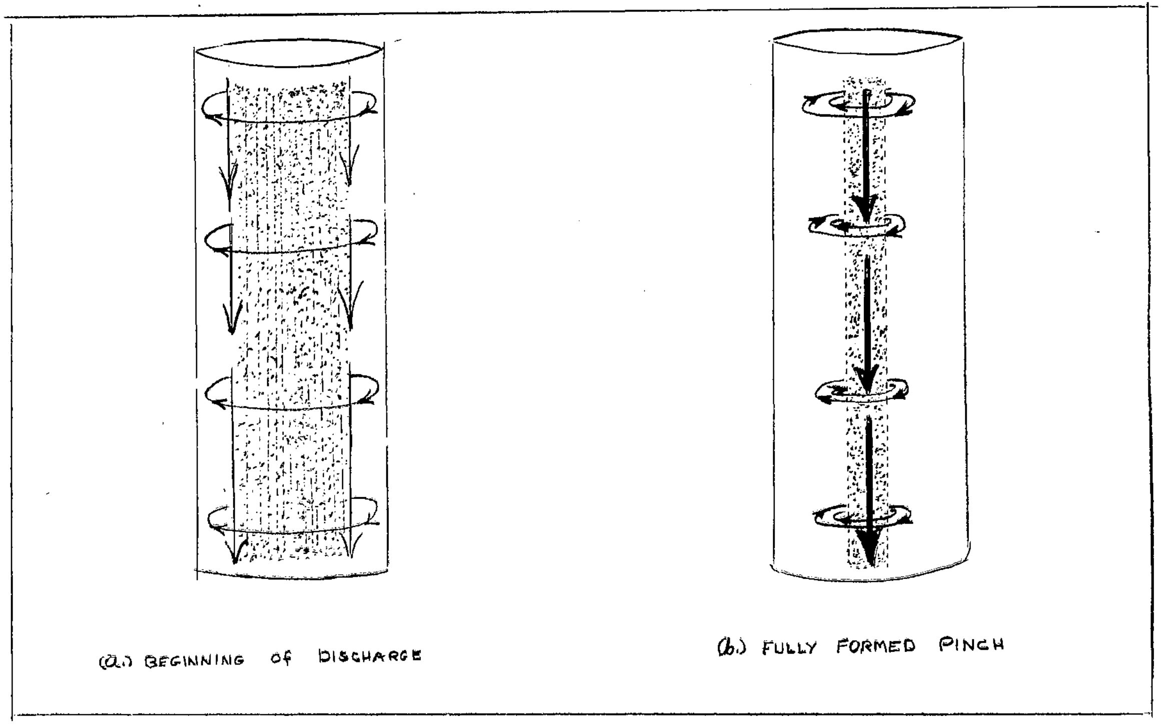


Figure 3. Plasma Pinch Sequence.

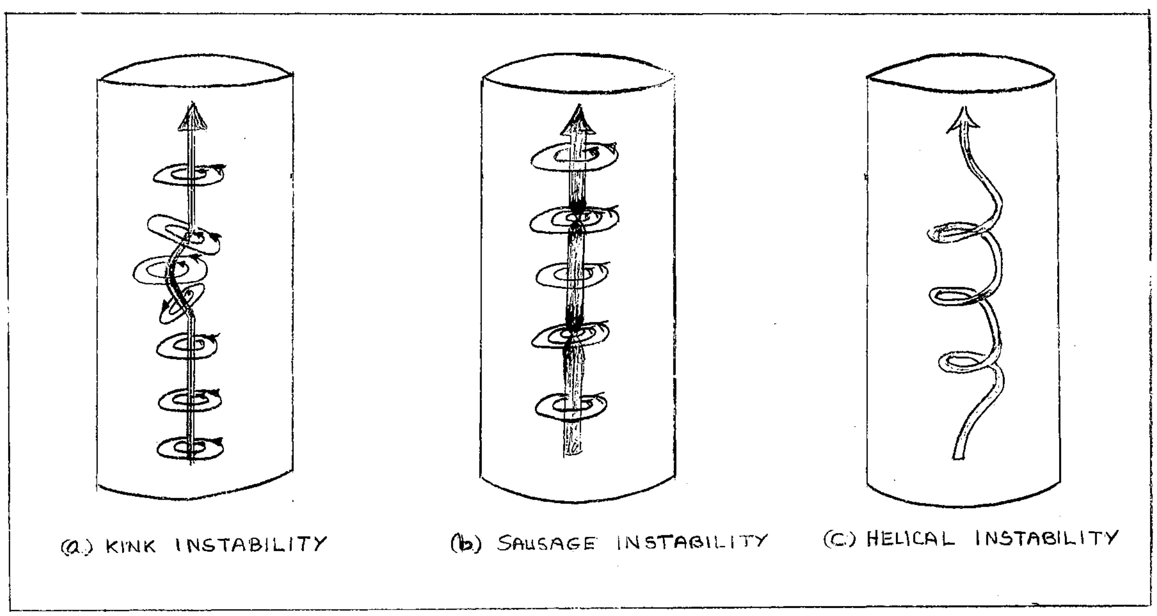


Figure 4. Types of Plasma Pinch Instability.

aggravated and to increase in magnitude. Such kink instabilities have been observed to result in the disappearance of the filament as it thrashes wildly against the walls by which contained; thus dissipating its energy. Further investigation has revealed that these instabilities may be of two types. The first of these, the sausage ($m = 0$) instability, causes the filament to break apart as links of sausages might do, and is illustrated in Figure 4.b. The second, the helical ($m = 1$) instability, assumes the shape of a corkscrew as depicted in Figure 4.c.

The implication that the sausage instability is the cause of many beaded lightning reports is obvious. Further speculation as to the effects of the helical instability are left to the imagination, since it does not entirely fit the requirement for a sustained plasma entity. However, it is interesting to note that accounts of "coiled" lightning are mentioned by Schonland, (20) although he attributes them to optical illusions.

This completes the coverage of those areas of study which have not received much, if any, consideration heretofore, in the study of atmospheric electricity. It brings us to the last, but very important area of knowledge upon which the MHD tornado concept is based--that of the similarity of the conditions existing in thunderstorms with those necessary for the occurrence of MHD phenomena.

## The Thunderstorm Cell

Although the methods for the electrification of thunderstorm cells are still subject to considerable debate, the actual charge distribution of the storm cloud is generally accepted. The result of this intense charging is that the possibility exists for various types of electric discharges, three of which are of particular interest in this investigation; the inner-cloud discharge, which is probably the result of the separation of positive and negative areas of charge within the cell; cloud-to-cloud discharges made possible by the proximity of opposite charges in different cells; and cloud-to-ground discharges which result from the proximity of the negatively charged cloud base to the positively charged surface of the earth or some structure upon it. The accepted cell charge distribution and these three types of lightning discharges are pictured in Figure 5. The mechanism of a lightning discharge is discussed in greater detail in Chapter III.

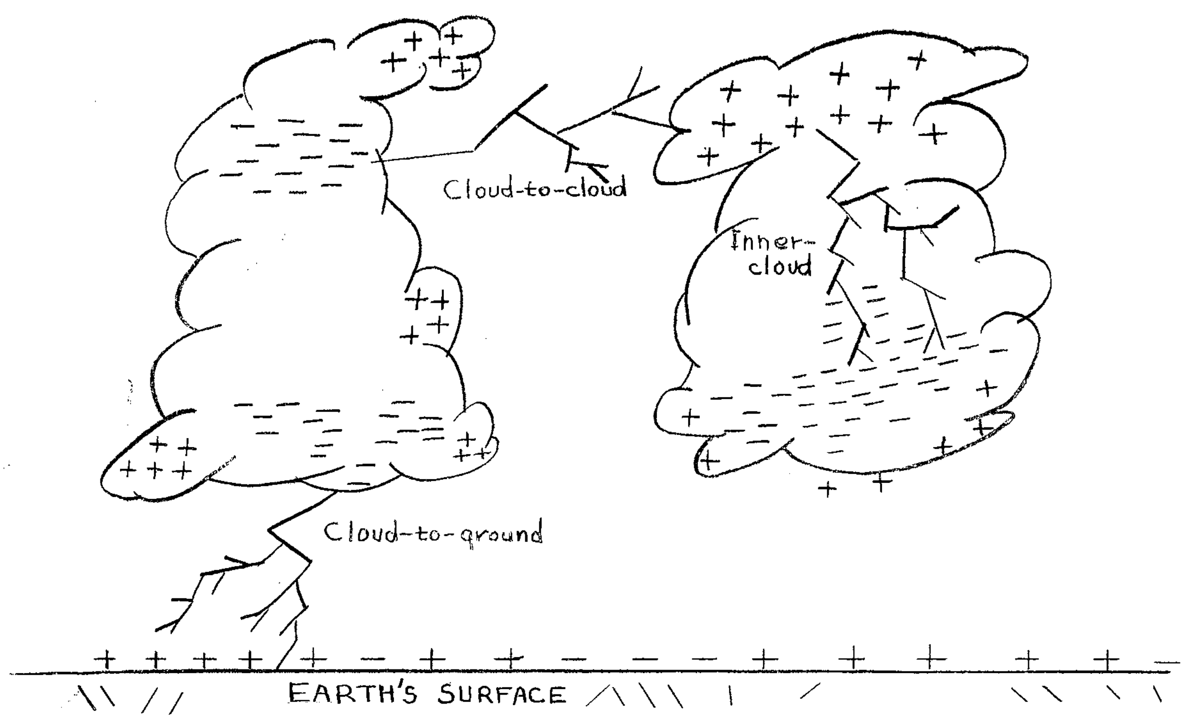


Figure 5. Charge Distribution and Lightning Discharge Types in Thunderstorm Cells.

Having accounted for the two MHD conditions of high voltage potentials and current discharges, we turn now to the required ingredient of an ionized gas. This is an obvious condition of thunderstorm development since the very nature of the atmosphere is conducive to high degrees of ionization, particularly when the water vapor of clouds may be considered as a possible source of hydrogen or deuterium. (27).

A final requirement, and again an obviously fulfilled one, is that of external magnetic fields. This, of course, is fulfilled by the ever present magnetic field of the earth and by the very probable presence of induced magnetic fields in electric storms. (5, 28).

This description of thunderstorm conditions has been very brief, in view of the many excellent references available on the subject. (8, 20, 23, 28, 29).

At this point in this dissertation it should be fairly obvious that MHD phenomena, as defined herein, do exist in active thunderstorms to some degree. The acceptance of any other theories presented, will, of course, depend upon the further development of sferics generation theory, and on the presentation and analysis of associated data contained in the remainder of this report.

# CHAPTER III

# THE SFERICS GENERATOR

In order to undertake an investigation of the mechanism by which sferics are generated, it is first necessary to examine the lightning discharge itself.

## The Leader Concept

Probably the greatest advance in understanding lightning was accomplished by Schonland (20) by using a rotating lens camera to photograph such discharges. These photographs demonstrated that lightning discharges occur in a series of rapidly recurring strokes usually too fast for the human eye to distinguish, and ranging in number from 3 to 12 strokes. (23). They also revealed that each stroke is a sequence of events which is generally known as the leader or streamer series, occurring in the following manner.

1. A dark leader stroke is present which can consist of either a stepped leader or a dart leader. The stepped leader is the more common as the initial stroke of a multiple series, but the dart leader takes its place on all subsequent strokes in the series. The stepped leader stroke is a series of relatively short paths zigzagging through previously unionized air, and traveling at a velocity of $5 \times 10^9$ cm/sec. However, due to a pause between each step of about 100 microseconds, the average velocity of the entire stepped leader stroke is about $5 \times 10^7$ cm/sec,

with each step on the order of 50 meters in length. It is this leader which gives lightning its commonly observed forked appearance as it wends its way from a charge area of one sign to a charge area of opposite polarity.

The dart leader does not show steps but proceeds directly to the opposite charge area, either as the initial breakdown path instead of a stepped leader, or, as the preceding stroke of each successive cycle of a multiple series. The velocity of the dart leader is about $2 \times 10^8$ cm/sec.

Both the stepped leader and the dart leader are classified as dark strokes, since, due to the overwhelming luminosity of a third type of stroke known as the return streamer, they are rarely observed by the naked eye except in some cloud-to-cloud discharges. It is generally accepted that the current density of both the stepped and dart leaders are about the same, being on the order of from $10^3$ to $10^4$ amperes. (30). It is generally believed that each step of a stepped leader is pre-ionized by a pilot streamer which has no luminosity whatever, carries a current of only about 1 ampere, and travels at a velocity of about $5 \times 10^7$ cm/sec. (4, 30). It is this invisible stroke which pre-ionizes the short stepped leader paths, losing its energy at the end until regenerated by the following short stepped leader stroke itself.

2. The main stroke, or return streamer, is that part usually called lightning due to the extreme brilliance which results from its 200,000 to 500,000 amperes of current. The velocity of the return streamer is about $3.5 \times 10^9$ cm/sec, with peak velocities observed on the order of $10^{10}$ cm/sec. (23, 30). This extreme current and velocity of propagation are due to the fact that this streamer travels over the already highly ionized path

created by the stepped or dart leader, and incidentally, in the opposite direction. It usually occurs when the stepped or dart leader has approached within 30 to 40 meters of the ground, or, in the case of inner and inter-cloud strokes, within an undetermined distance from its oppositely charged destination.

The difference in current densities and velocities of propagation of the various leaders and streamers could possibly be of great significance in the process of sferics generation, and will be discussed in greater detail later in this chapter.

The occurrence of both a stepped or dart leader and a return streamer in all types of lightning discharges is the subject of some doubt--according to Schonland. (20). Following the next section it will also be made the subject of some controversy.

## Impulse Breakdown Streamers

Loeb, (30) in his considerable research on sparks in air, has compared the lightning stroke mechanism just described, to a positive streamer spark in air under impulse overvoltage conditions. If we have two parallel electrodes and an impulse overvoltage is applied, any free electrons present, or made available by even a single photoionization, will result in an avalanche of electrons from the cathode toward the anode--due to the regenerative photoionizations and ionic collisions of the initial particles. This electron avalanche includes both electrons and the positive ions remaining from the accumulative ionization of its forward progress. The more mobile electrons precede the positive ions in the form of a negative tip of the avalanche, with an average velocity of the entire cloud having been observed under laboratory conditions as approximately 2 x $10^7$ cm/sec (remarkably similar to that of the previously discussed pilot streamer, and fairly close to that of stepped and dart leaders). Upon reaching the anode, the front running electrons are literally swallowed up by the anode, leaving a positive space charge behind and effectively increasing the anode field. This cloud of positive ions now begins to move back across the gap toward the cathode, creating more electrons by ionic collision and subsequent photoionizations, and traveling at observed velocities sometimes greater than $10^8$ cm/sec, a speed not too much less than that of the return stroke of the lightning discharge. As this positive streamer advances, the newly produced electrons are fed into the positive ion channel both laterally and from the tip, creating a condition of electric conductivity in the channel, and an intensely high electric field at the advancing tip. This high electric field results in both the observed rapid advance of the streamer and in a bright pip of light caused by further intense ionization. Another area of luminosity back along the channel is the result of less intense radial ionization processes or could possibly be the result of a plasma pinch.

At extremely high impulse voltages, a slightly different process was observed, in that the electron avalanche assumed a spindle shape at mid-gap, sending a positive streamer back to the negative electrode and a negative streamer forward to the anode.

It should be noted here that in both the electron avalanche and the positive return streamer, the electrons were traveling in one direction; i.e., from cathode to anode; but that the positive ions traveled from cathode to anode as part of the electron avalanche, and then from anode to cathode as the positive streamer--each of these directions at a different speed.

Loeb (20) points out that the greater velocity of advance of the positive streamer over the electron avalanche stems from the conservative nature of the positive streamer, in that it draws the nimble electrons into or along its nearly immobile positive charge instead of outwardly dispersing them as from the negative cloud. It follows then that the electrons too, travel at two different speeds; the second (positive streamer flow) being the greatest due to the already ionized path of advance. If we assume the generally accepted convention of current flow opposite to that of the electrons, then the uni-directional electron flow of the impulse arc gives us a flow of current from anode to cathode; and thus does not violate any previously established laws of electricity, regardless of the different velocities of propagation.

These points on varying velocities of propagation and the positive ion bi-directional characteristics, are again stated as being of possible significance in the generation of sferics--particularly in view of the possibility of positive ion and electron oscillations in plasma, as discussed in Chapter I.

In comparing the just discussed impulse voltage arcs with lightning strokes, it is reasonable to assume that the greater conductivity of the moisture laden air of thunderstorms would increase the velocities of propagation of both the electron avalanche and the positive streamer; such that they would compare favorably with the velocities of the stepped or dart leaders, and the return streamer, respectively. Loeb (30) gives a relatively simple but thorough mathematical explanation of this in his referenced works.

The investigative theory, analysis of data, and the conclusions of this dissertation are based on the premise that the impulse breakdown arc and the lightning discharge process are basically identical--the only differences being in the voltages and currents involved and the lack of solid state electrodes of perfect geometric configuration in thunderstorm cells.

## Sferics Generation Possibilities

Before analyzing the possibilities of certain phases of lightning discharges as sferics generators, it is necessary to take a stand on cloud-to-cloud or air discharges--as Schonland (20) put it. He has stated that when air discharges are recorded on moving-lens cameras, they consist mainly of stepped leader processes with occasional bright dart leaders following up along channels already formed, and that since they make no contact with the ground, they show no return streamers.

This observation by Schonland, although probably true in many cases when air discharges are the result of naturally occurring strings of highly ionized air caused by turbulence effects, does not logically hold true when a true cloud-to-cloud stroke occurs, since such a discharge would be effectively between two electrodes of opposite polarity and would necessarily include a return stroke of positive ions. Observations of intense air discharge displays during the course of this investigation, tend to support this view, in that although the thin bluish-white and very forked air discharges of Schonland were observed, heavy straight arcs of short length and blinding brilliance were also seen to occur between highly developed adjacent thunderstorm cells--thus indicating that the return stroke phenomenon is not necessarily missing in all air discharges.

Returning now to the various phases of the impulse arc, let us analyze the various possibilities for the electromagnetic propagation of sferics signals. From the knowledge thus far gained, these are now listed.

1. If the relatively confined path of a multiple discharge is considered as a thin wire antenna, the resulting sferics may be the result of the current flow (electronic or ionic) along this antenna, with the various frequency contents determined by either one of or a combination of the following parameters:

a. Length of the channel.

b. Velocities of electron advance.

c. Electron oscillations in the antenna plasma as groups of electrons move forward at various speeds.

d. Velocities of positive ion advance.

e. Positive ion plasma oscillations under the same conditions as 1.c. above.

f. Radiated energy of photoionization or ionic collision processes along the antenna length.

2. The reversing process of the electron avalanche as it reaches the anode, possibly generating a signal through the sudden appearance of the positive ion space charge.

3. The probable intense field distortion as the returning positive streamer approaches the cathode, could theoretically produce a multi-frequency signal of fortuitous individual frequency content.

4. A fourth possibility may be the establishment of an instantaneous MHD standing wave capable of direct conversion to an electromagnetic signal. This may be closely associated with the plasma oscillation possibilities mentioned in 1.c. and 1.e. above, and carries with it the additional

significance that such standing waves would also be possible in a plasmoid-- at a sustained and uniquely identifying frequency.

5. A final existing possibility is that none of the above listed processes have anything to do with the generation of sferics, and that such signals are instead generated by some process as yet unstudied in the wave propagation field.

## Investigative Approach

In view of the numerous possibilities just listed, it was decided to attempt a correlation of the sferics content of each of the three types of lightning strokes herein considered. Such an investigation would tend to either eliminate or lend support to some of, or portions of, the listed sferics generation possibilities; thus narrowing down the area of future research on this problem.

It should be noted here that since certain of the listed possibilities inherently depend on degrees of ionization, then any evidence or data supporting those possibilities would also lend support to the possibility of MHD phenomena in connection with the generation of specific types of sferics.

# CHAPTER IV

## METHOD OF INVESTIGATION

The method chosen to investigate the stated problem was particularly simple, and to some degree, repetitious of that of Roemer. (31). Briefly, it consisted of the visual observation of cloud-to-ground, cloud-to-cloud, and inner cloud lightning discharges and the correlation of each specific type to the sferics data being simultaneously recorded by electronic equipment. The visual observations were correlated with the electronic data through the use of a simple electric hand switch, this being the fundamental departure from Roemer's (31) method, in that he used a camera to photograph the lightning stroke series. However, the use of the manual switch in this case was superior to the camera, in that the observations taken were not limited to a particular area of lens coverage, and, in addition, allowed for discriminating sampling techniques.

### Evaluation of Method

Two inherent weaknesses existed in the manual recording technique, in that human reflex time had to be considered in the correlation efforts, and in that the marking pulses were not recorded on the sferics recording film, but rather on the Brush Recorder tape used in conjunction with a concurrent investigation on changes in the earth's electric field. (32). However, both the sferics film and the recorder tape were being electronically marked from a single calibrated time source; thus relegating the timing correlation to a matter of the labor involved in the transfer of events from one record to the other. The human reflex time error was negated by the fact that the discharges picked for correlation were sufficiently spaced in time to prevent overlapping, in most cases. In addition to this, the recording tape of the electric field fluxmeter aided in this correlation in that most of the observed lightning discharges also registered as electric field variations; thus giving an exact indication of the human reflex time involved in each recording pulse.

## Equipment Used

The equipment used for the reception and recording of the sferics in this investigation consisted of a sferics waveform receiver, low frequency direction finder, high frequency direction finder, and recording equipment which included oscilloscopes, a timing device and a recording camera. This is only a small part of the equipment in use at the Oklahoma State University Tornado Laboratory, and most of which is described in complete detail in the doctoral thesis of the original project engineer, R. D. Kelly. (33). This equipment is designated as Q-3 equipment and is designed to receive sferic electromagnetic radiation energy at various frequencies between 3 kilocycles and 10 megacycles. The recorded data can include the time of arrival, angle of arrival, and the waveform and received energy levels at 10, 75, and 150 kilocycles.

Figure 6 shows an overall signal circuit pictorial diagram as adapted from Roemer. (31). A number of narrow band receivers give the Q-3 equipment the additional capability of indicating the energy content of the sferics waveform at the particular frequencies to which these receivers are tuned. One of the receivers was tuned to a frequency of

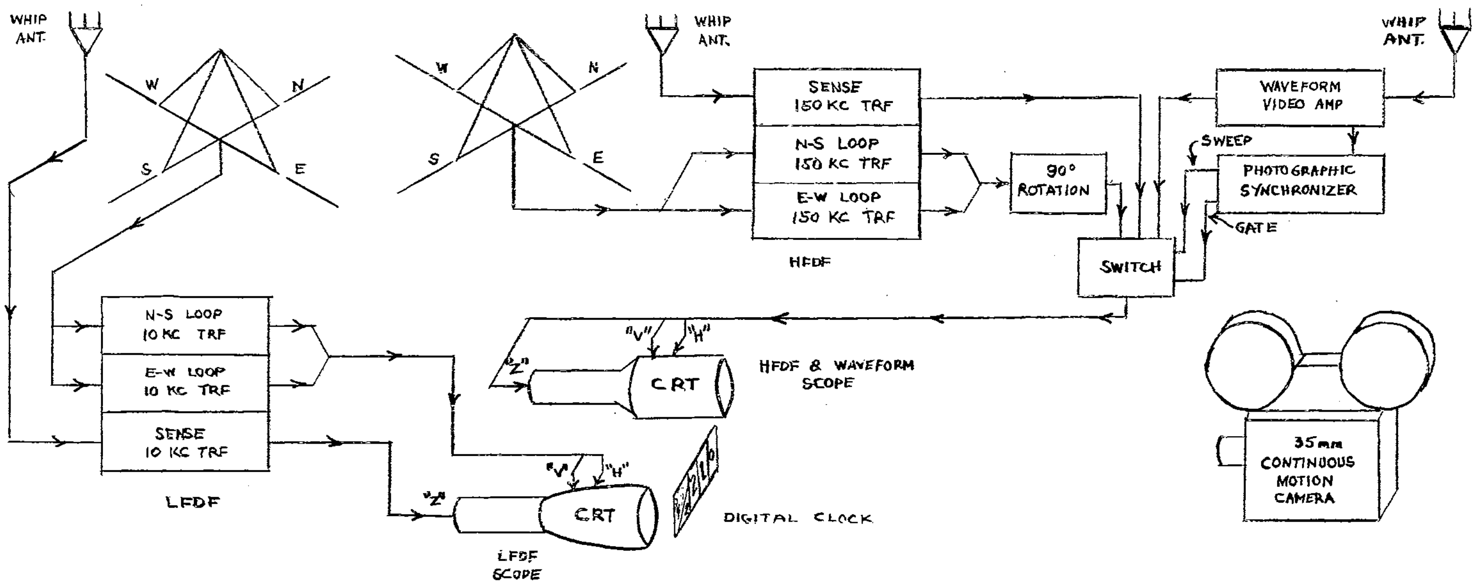


Figure 6. Pictorial Diagram of Q-3 Equipment.

20 kilocycles during this investigation, resulting in some unexpectedly significant data.

The sferic signals are received by vertical antenna sections with outputs of 3 to 300 kilocycles, and 5 to 10 megacycles. These two outputs are then fed to the calibration section--the 3 to 300 kilocycle signal then being sent to a direction finding section to be used as a sensing signal for elimination of directional ambiguity produced by the direction finding loop antennas of that section. This signal is also connected to the waveform section and to two low frequency narrow band amplifiers in the frequency sampling section. The 5 to 10 megacycle signal is also connected to a direction finding section and to the high frequency narrow band amplifier of the frequency sampling section.

The high and low frequency direction finding sections also receive the radiated sferic signals but by means of pairs of loop antennas tuned to frequencies of 10 and 150 kilocycles respectively. These signals are then amplified, corrected for directional ambiguity, and prepared for presentation on two, two-beam cathode ray tubes; and indicating, by their amplitudes, the energy of the individual frequency components, and the angle of arrival of the sferic pulse.

The wave form section receives the actual multi-frequency waveform of the sferic pulse, preparing it for presentation on one of the cathode ray tubes (that which also displays the high frequency information). This waveform appears on the CRT as one sweep of a ten step raster and is separated by the space difference between the consecutive sweeps of the raster. At the end of the tenth step, the raster will be completed and a new one initiated by the eleventh pulse.

A timing section provides both timing information to the recording section, and calibration frequencies to the calibration section. The frequency standard provides a 100 kilocyle signal to a frequency divider, which, in turn, provides a 100 kilocycle and a 10 kilocycle calibration signal to the calibrator unit. A 100 cycle per second voltage is fed to the motor of a synchronous timing device containing one and six second switch contacts to provide indicator pulses to the other CRT (that which displays the low frequency data). The six second pulse is also used to illuminate a digital clock face for photographic purposes. A receiver, capable of receiving National Bureau of Standards radio station WWV, and a WWV calibrator unit are also provided as part of the timing section, in order to compare the local timing system against the WWV standard reference.

The recording section consists of a camera box and a variable speed strip film camera in which the faces of both oscilloscopes and of the timing clock are photographed on continuous 35mm film. Figure 7 is a drawing of a typical film strip illustrating the location of the various bits of information on the sferics film.

A description of the electric field fluxmeter and its Brush Recorder is not pertinent to this presentation, but is covered in the doctoral thesis of Boudreaux. (32). Suffice it to say that the correlation of the Brush Recorder tape with the sferics film, was accomplished solely by noting the desired event times on the tape and then checking at those specific times on the film.

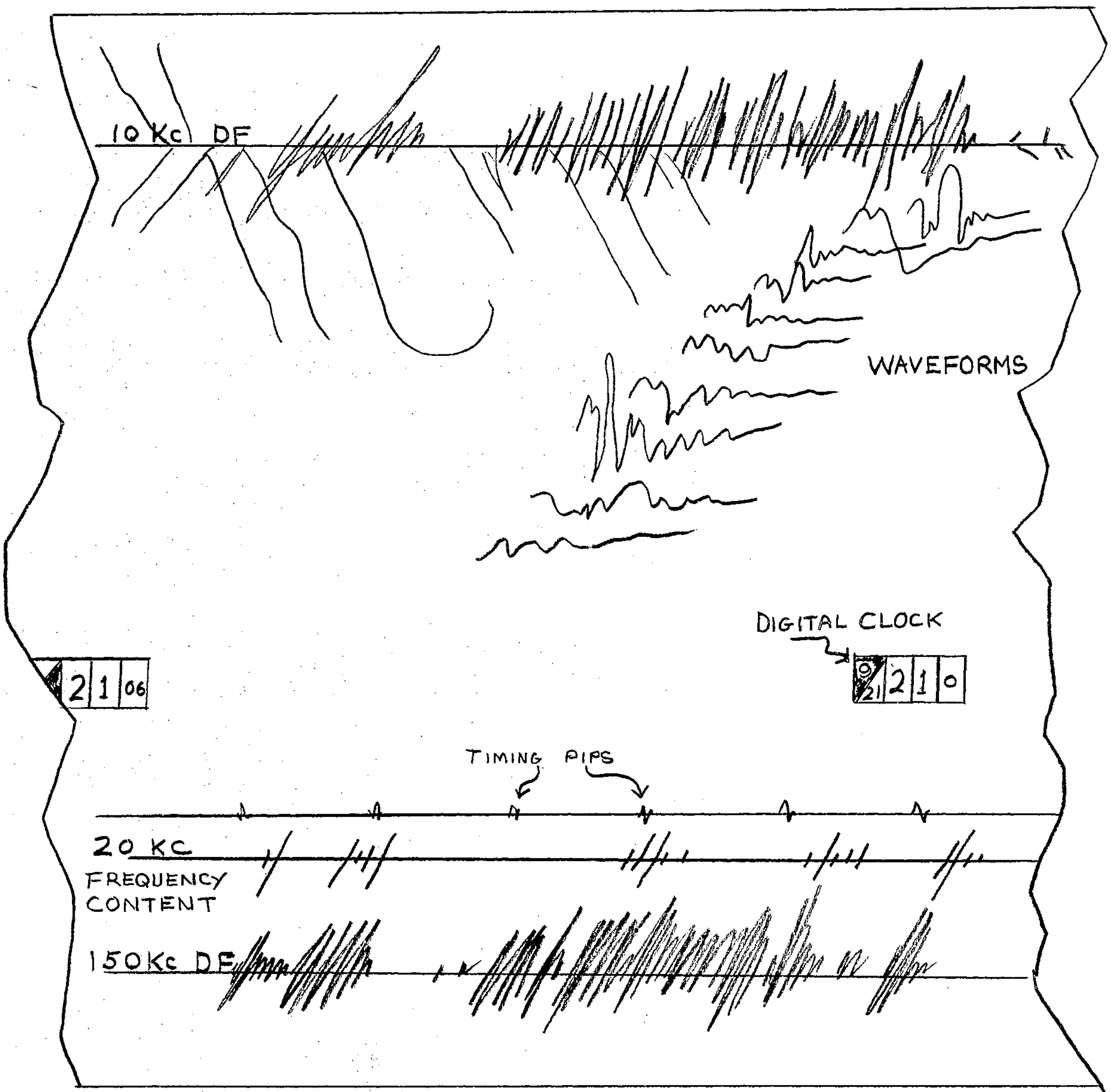


Figure 7. Film Record fron Q-3 Equipment Illustrating Location of Information.

# CHAPTER V

# DATA AND ANALYSIS

Since the laboratory work of this investigation was dependent upon the natural occurrence of thunderstorms or tornadoes, it was necessary to first set up the measuring equipment, and then to wait for any such fortuitous occurrence (in the case of severe storms, fortuitous only in the eyes of an investigator of such phenomena). The Spring of 1960 did produce a series of such storms in Oklahoma, resulting in ample data to justify this investigation.

## Obtaining the Data

The major portion of the data recorded and analyzed herein, was obtained during two specific thunderstorm situations, one of them classified as a severe storm. The first was a situation in which a line of fairly active thunderstorms passed approximately 20 to 30 miles south of the tornado laboratory and moving from west to east. This situation occurred in the early morning (dark) hours of April 14, 1960, and provided an excellent opportunity for the correlation of recorded sferics with the visually observed and specifically identified types of lightning discharges which generated them. This opportunity was the result of the complete absence of any cloud cover between the observer and the line of storms, and as a result of the well spaced and easily recognized lightning discharges, which, in most cases, were isolated and well defined.

Due to the adequate spacing between discharges, it was possible to record written comments on the individual characteristics of these discharges; i.e., "long streamer across sky"; "isolated heavy cloud-to-ground"; "cloud-to-ground followed by two cloud-to-cloud from same storm cell". When coupled with the coded pulses of the observer's hand switch, these comments allowed a choice of examples of absolutely identified discharge types for presentation of the oscilloscope photographs of Figures 8 through 13.

The second thunderstorm situation occurred on the night of April 15, 1960, just after sunset, and passed directly over the tornado laboratory. It was a severe storm which exhibited many of the characteristics of a potential tornado oscillator--these characteristics including the familiar hook shaped roll cloud, observed in this case, on the screen of the laboratory radar equipment. Unfortunately, the sferics counting recorder of Jones and Hess (13) was undergoing repairs at the time of the storm, and complete correlation of the other, less immediately identifiable data, had not been completed at the time of this writing. Suffice it to say that the storm was characterized by rapid overland movement, extreme vertical "anvil top" development; vivid displays of inner-cloud, cloud-to-cloud, and air discharges; and included inch diameter hail and strong winds which literally tore one door of the laboratory off its hinges. The above mentioned cloud-to-cloud and air discharges were of both the heavy brilliant return streamer type; and the coiling, spiraling, or multi-forked dart and stepped leader type. Unfortunately, most of the latter type, which apparently was concentrated along the front surface of the squall line, passed over the laboratory before the equipment had been put into operation and calibrated for timed observations. However, the apparent effects of these air discharges are pointed out later in the analysis portion of this chapter. Sferics data on this storm is presented in Figures 14 and 15.

Presentation and Analysis

The selected photographs of the Q-3 oscilloscope faces presented herein, were taken at a camera speed of 22.2 inches per minute, and, in addition to the individual identifying captions, are further clarified by vertically directed lines labeled a, b, c, etc., for the purpose of pointing out specific areas of significance in the analysis of sferics generation possibilities. In all cases, approximately six seconds of time are displayed, as indicated by the second marks on the time line; time running from right to left. In most cases, the waveform data was deliberately attenuated to prevent excessive film clutter due to the comparatively low camera speed. Reviewing Figure 7 briefly; the top line of the photographs shows the directional 10 kc sferics content, the directionality indicated by the azimuth of the individual pulses around their points of origin on the line; the bottom line pictures the 150 kc content, also directional; the first line below the sequence clock face is the time line, with a major pulse at each second; and the line just below the time line represents the non-directional 20 kc sferics content, which, as will be pointed out, did contain information of possible significance in future research.

Turning now to these photographs, Figures 8 and 9 illustrate two examples of isolated and well defined cloud-to-ground discharge sferics. The most obvious point of interest in both figures is the presence of both 10 and 150 kc energy content in each surge or stroke of the discharge.

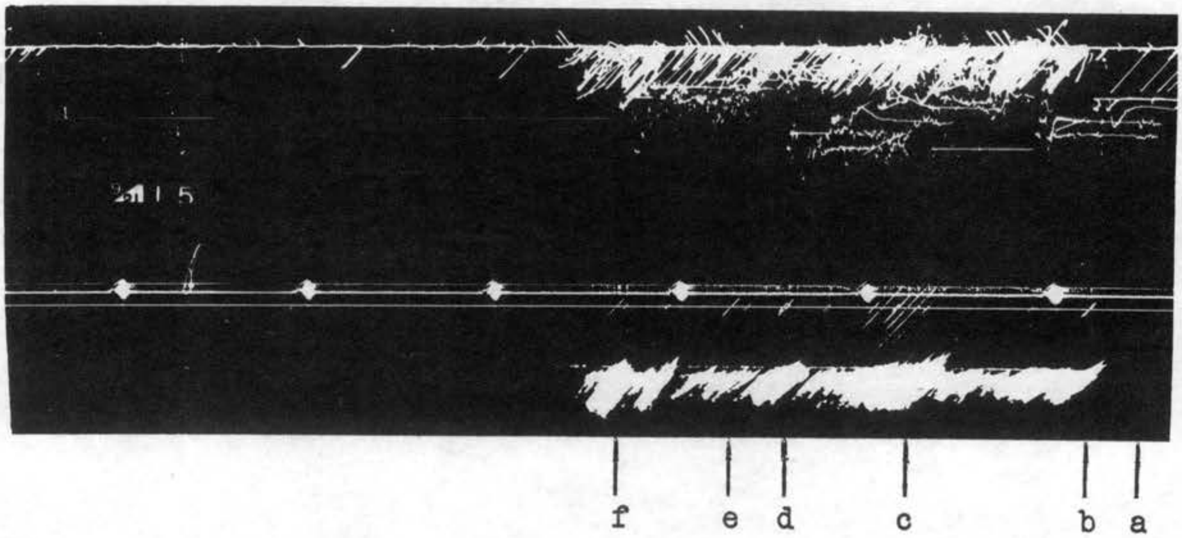


Figure 8. Sferics of a Cloud-to-Ground Lightning Discharge, 14 April 1960.

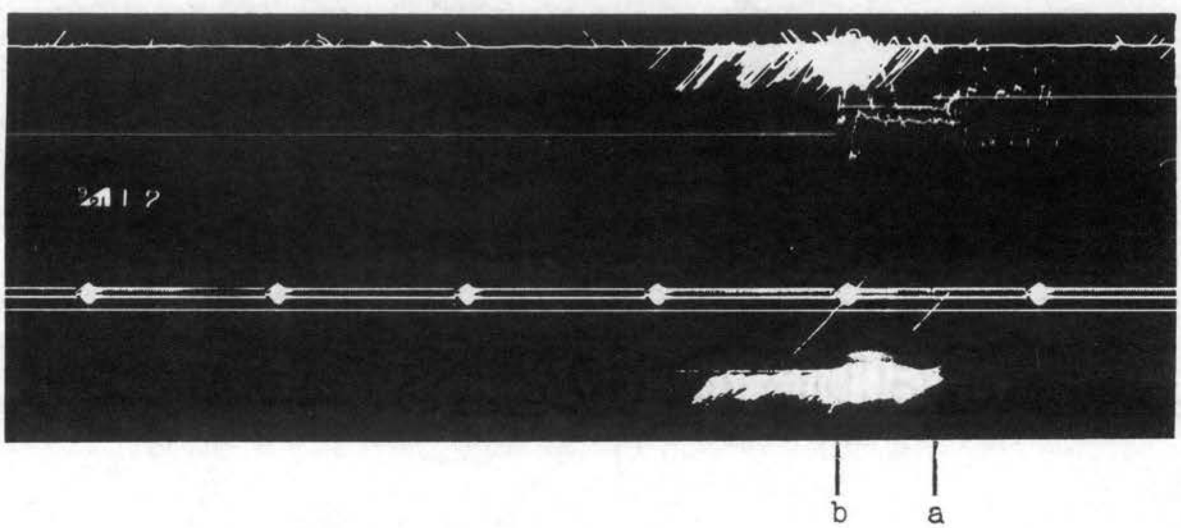


Figure 9. Sferics of a Cloud-to-Ground Lightning Discharge, 14 April 1960.

An additional point of significance is the presence of a few 10 kc pips at point a in Figure 8, these pips preceding the main discharge cycle, but from the same apparent direction and in the same amplitude range. This may be an indication that the dart or stepped leader processes leading up to the initial stroke of the series, are responsible for the generation of the 10 kc energy content.

Another area of possible significance is the appearance of 20 kc energy bursts at various points throughout the discharge and apparently associated with the major surges of the 10 and 150 kc discharges. This is particularly obvious at points b, c, d, e, and f of Figure 8; and at points a and b of Figure 9. Accurate alignment of the initial 20 kc pulses in both pictures indicates that they may occur just prior to the initial pulses of both the 10 and 150 kc discharges; and thus presumably in the same sequence throughout the discharge cycle.

Figures 10 and 11 illustrate two examples of well defined and isolated cloud-to-cloud discharges. Figure 10 is particularly interesting in that the discharge itself was classified as having "terrific" streamers across the sky for some distances. Again, the most obvious point of significance is the generation of both 10 and 150 kc signals by this typs of lightning--this point being repeated, as it will be throughout this section, to emphasize the fact that the generation of either 10 or 150 kc sferic signals is apparently <u>not</u> a function of the <u>type</u> of discharge; that is to say, cloud-to-ground discharges do not generate predominantly 10 kc sferics, nor do cloud-to-cloud discharges <u>normally</u> generate sferics predominantly in the 150 kc range--as was previously believed. (31).

Returning now to Figures 10 and 11, Figure 11 again shows an area of independent 10 kc energy around point e. This occurs following the main

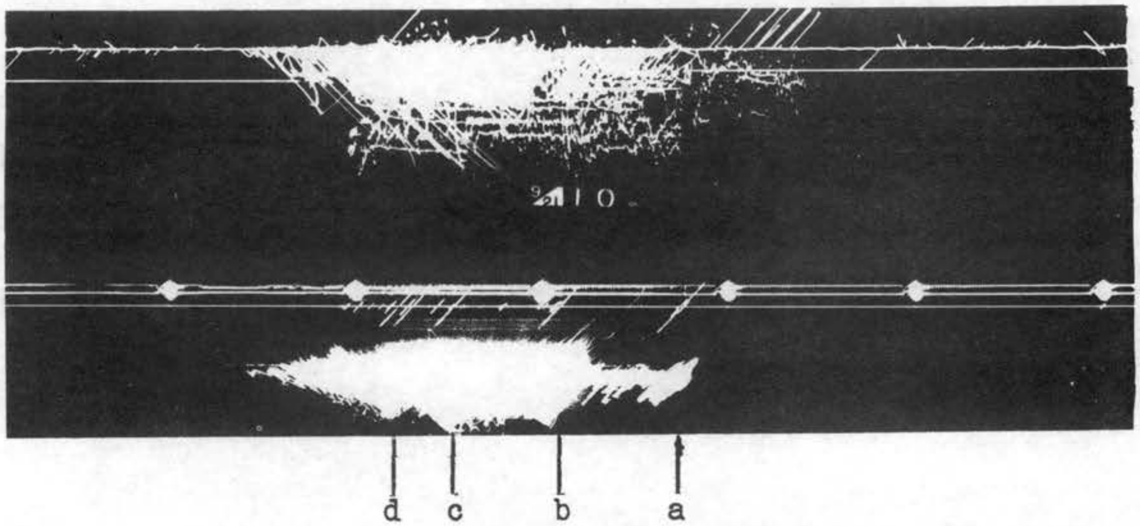


Figure 10. Sferics of a Cloud-to-Cloud Lightning Discharge, 14 April 1960.

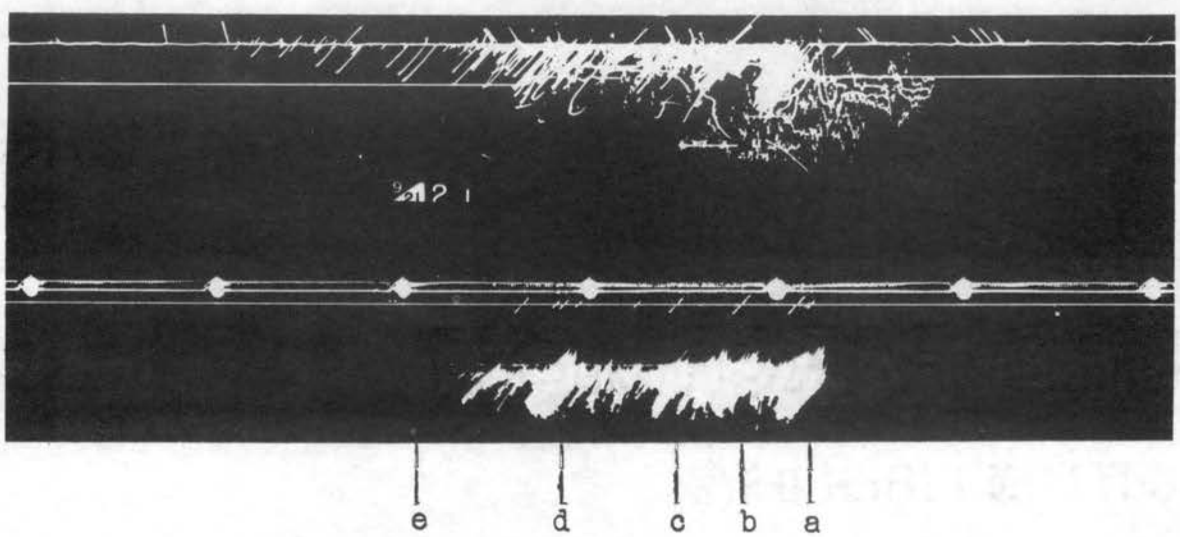


Figure 11. Sferics of a Cloud-to-Cloud Lightning Discharge, 14 April 1960.

discharge cycle, in contrast to Figure 8, where it occurred prior to the discharge. It may be an indication of the presence of Schonland's (20) air discharge dart or stepped leaders, attempting to maintain the original cloud-to-cloud discharge even after the area of return stroke potential has been drained of its initial charge.

Again, as in the case of Figures 8 and 9, Figures 10 and 11 both indicate surges of 20 kc energy at points a, b, c, and d, and apparently corresponding to surges in the 10 and 150 kc bands. Accurate alignment of the initial 20 kc pulse, again indicates a possibility of the occurrence of this signal just prior to the first 10 and 150 kc strokes. Expanding on this point for a few moments, the following possible explanation is presented. Since the presence of both 10 and 150 kc energy, in both cloud-to-ground and cloud-to-cloud discharges of vastly different lengths, negates the length of discharge as the determining factor in frequency content generation; then there is a strong possibility that the velocity of travel of groups of either electrons or positive ions, is that determining factor. Furthermore, since the stepped or dart leader, with its slower velocity of advance, appears to be a possible source of 10 kc energy alone, then it follows that the faster traveling return stroke would generate the 150 kc signal. It then follows that the 20 kc signal may be the result of an initial, momentary increase in velocity of the group charge, as the result of intense field distortion at one or the other ends of the discharge path--this distortion due to electrode proximity effects discussed by Loeb (30) in his referenced works.

Figures 12 and 13 illustrate examples of oft recurring series of cloud-to-ground and cloud-to-cloud discharges observed during the storm

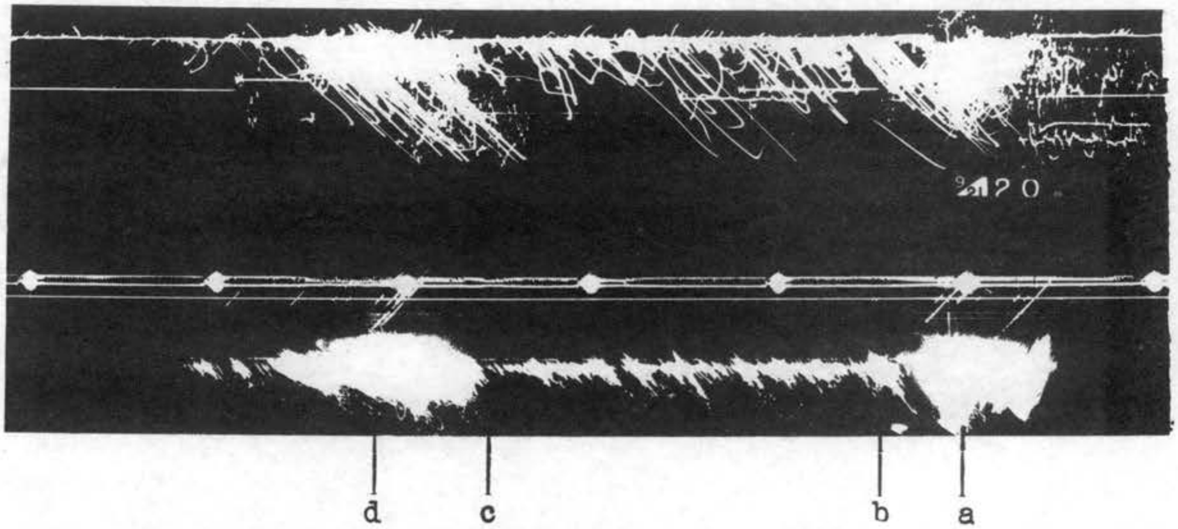


Figure 12. Sferics of a Multiple Discharge Lightning Display of One Cloud-to-Ground and Two Cloud-to-Cloud Discharges, 14 April 1960.

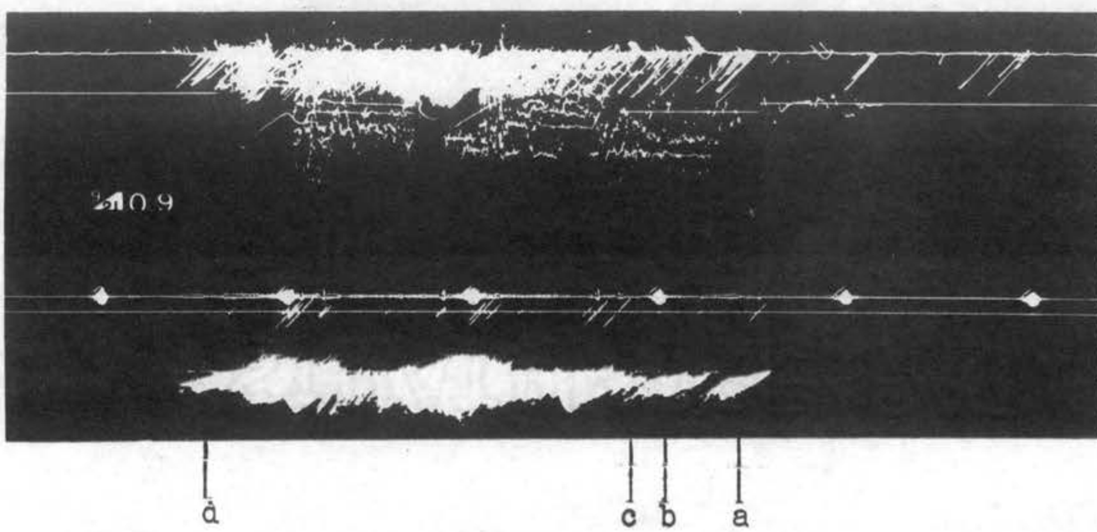


Figure 13. Sferics of a Multiple Discharge Lightning Display of One Cloud-to-Ground and Two Cloud-to-Cloud Discharges, 14 April 1960.

of April 14. Figure 12 shows a cloud-to-ground discharge at point a, followed by a moderate cloud-to-cloud discharge between points b and c, and then by a heavy cloud-to-cloud burst at point d.

Figure 13 shows a cloud-to-ground discharge at point a, followed by a moderate cloud-to-cloud series at b, and a heavier cloud-to-cloud series between c and d.

Again, the correlation of the 10, 150, and 20 kc signal content follows the same patterns, except that the 10 kc amplitude in the first cloud-to-cloud discharge of Figure 12 (points b to c), seems to be extremely large, while the amplitude indications of 20 kc energy have almost disappeared.

Up to this point in the presentation of data, the inner-cloud lightning discharge has been purposely neglected due to the fact that no absolutely identifiable inner-cloud strokes were observed. Such positive identification was prevented by the vast areas of vertical development in both storms, making it impossible to distinguish between hidden (behind clouds) cloud-to-cloud or air discharges, and actual inner-cloud discharges. (Apparently the best situation for such observations would be during the occurrence of isolated thunderstorms, rather than squall lines.) However, the data taken on the storm of April 15 was visually determined to contain apparent inner-cloud discharges, some of which will now be presented in Figures 14 and 15.

Figure 14 shows a series of cloud-to-cloud and inner-cloud discharges, with a cloud-to-cloud at points a and b respectively, and three inner-clouds at points c, d, and e respectively. Although each of these discharges is fairly well defined at the 10 kc level, it is interesting to note that a unidirectional 10 kc signal, of extreme

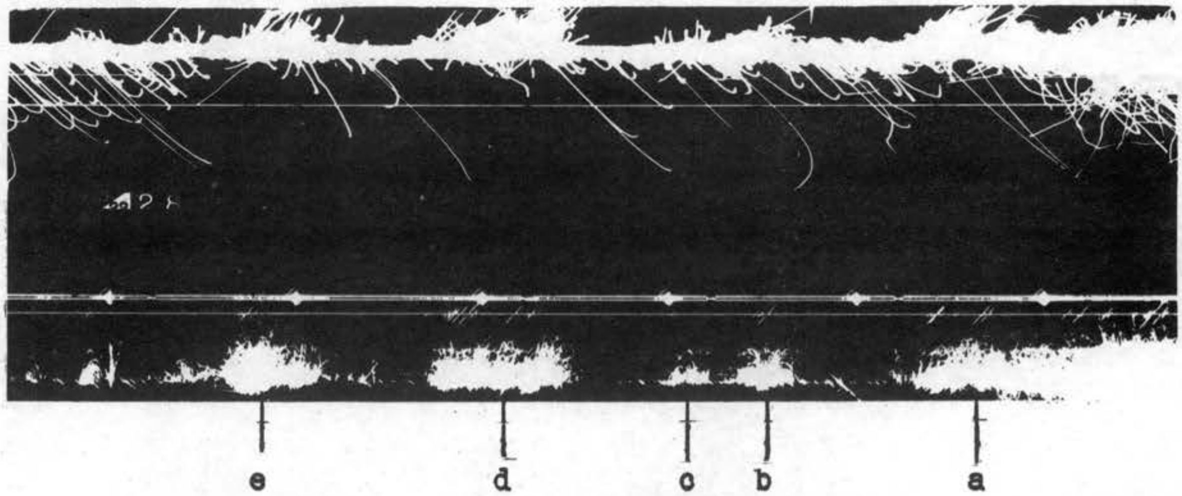


Figure 14. Sferics of a Multiple Discharge Lightning Display of Two Cloud-to-Cloud and Three Inner-Cloud Discharges, 15 April 1960.

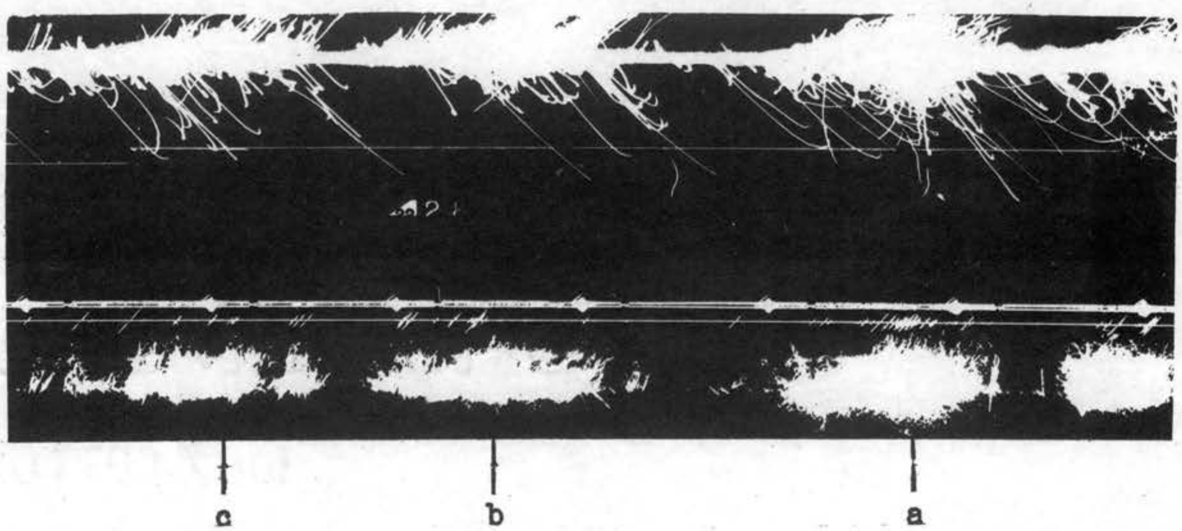


Figure 15. Sferics of a Multiple Discharge Lightning Display of One Cloud-to-Cloud and Two Inner-Cloud Discharges, 15 April 1960.

amplitude and ellipticity, occurs continuously and in addition to, the 10 kc signals associated with the individual discharges. This is particularly noticeable between the first and second discharges. It could be an independent signal from a distant storm but for the fact that its very amplitude suggests a definite proximity to the storm area under observation, which, at that time, was almost directly overhead. As mentioned previously, this could have been the sferics produced by the dart and stepped leader air discharges at the front surface of the squall line.

Figure 15 also depicts a series of cloud-to-cloud and inner-cloud discharges, with a cloud-to-cloud at a, and two inner-clouds at b and c respectively. Again the pattern of frequency correlation occurs, but the uniformity of the individual discharges suggests a trend toward the establishment of possible tornado oscillator conditions.

Two final notes of observation on Figure 14 and 15 are first; that the 20 kc pulses again appear to follow the 10 and 150 surges; and that there was a definite lack of any cloud-to-ground lightning discharges during this storm.

## CHAPTER VI

## SUMMARY AND CONCLUSIONS

It has been the general purpose of this thesis to investigate the possibility of determining an absolutely unique electromagnetic characteristic of tornado spawning thunderstorms. The specific investigatory efforts were directed at the lightning discharge as a sferics generator, in an attempt to correlate the predominant energy levels of these sferics with the types of lightning discharges which produced them. The results of these investigatory efforts were then compared to the hypothesized sferics generation possibilities listed in Chapter III, in an effort to narrow down these possibilities by either elimination or augmentation.

The results of this investigation and analysis of data indicate that there still exists the possibility that a tornado could be the result of magnetohydrodynamic phenomena in severe thunderstorms. Future investigations on this possibility may uncover the information needed for the positive identification and tracking of potential tornadoes--the necessary prerequisites for timely and adequate warning of impending disaster.

### Conclusions

Based on the study of the correlated data contained in this thesis, several conclusions can be stated.

1. Cloud-to-cloud, cloud-to-ground, and, presumably, inner-cloud lightning discharges <u>normally</u> generate sferics containing 10 kc, 20 kc,

and 150 kc frequency content. This eliminates the possibility that the length of the discharge path for these various types of lightning is a factor in the generation of a particular frequency content.

2. The occasional appearance of sferics containing only 10 kc energy, in thunderstorms devoid of cloud-to-ground lightning discharges, suggests that the stepped or dart leader may be responsible for the generation of this frequency content--this conclusion based on the occasional occurrence of partial discharges in which a return streamer is not propagated.

3. Based on the above conclusion, the 150 kc energy content is then generated by the return streamer; thus accounting for the appearance of both 10 and 150 kc energy in most lightning discharges.

4. The generation of a 20 kc signal by each apparent stroke of a lightning discharge, suggests either a third sferics generating mechanism, or, is the second harmonic of the 10 kc signal. It would then follow that a 300 kc second harmonic of the 150 kc content should also be present.

5. If the 10 and 150 kc signals are generated by two different lightning stroke processes; i.e., the dart or stepped leader, and the return stroke; then the difference in frequency generation must be due to either the difference in velocity of propagation of these leaders along the discharge path, or to the difference in the current density associated with each process.

6. Since both the velocity of propagation and the current density of these processes is determined by the conductivity or degree of ionization of the discharge path, then the appearance of predominantly 150 kc sferics in a tornado oscillator would indicate an intense area of sustained ionization--thus establishing the possibility for the occurrence

of MHD phenomena.

7. The possible existence of sustained MHD reactions in tornado oscillators would then indicate the possible existence of MHD standing waves--these waves representing an absolutely unique characteristic of the hypothetical MHD tornado.

## Recommendations

Research based on purely hypothetical conclusions can only lead to considerable wasted effort if applied exclusively or attempted too often. However, occasional postulation can be a great stimulus to sounder and more substantial research efforts, even if the postulation is erroneous. This thesis has included considerable postulation which has been deliberately included to provoke some thought on a new area of research. Nevertheless, it has also included the presentation and analysis of data which is applicable to present problems of research on atmospheric electricity. In view of this, several recommendations can be made on possible future research.

1. An attempt should be made to correlate definitely identified inner-cloud discharges with their generated sferics.

2. Further identification of the source of sferics containing only 10 kc energy is highly desirable and could prove or disprove many of the conclusions contained herein.

3. Further attempts should be made on the investigation of the 20 kc, 75 kc, and 300 kc sferics content.

4. Some effort should be made to repeat these investigations with the camera set at much higher speeds, to determine the exact time sequences of each initial stroke of a major discharge.

5. The investigation of sferics generation by groups of charged particles lends itself to actual laboratory conditions. Such research would do much toward determining the exact nature of the sferics generator and its relation to the occurrence of tornadoes.

6. In view of the many theories on tornadic generation based on heat processes, it would seem justifiable to attempt an investigation on the possible existence of areas of intense sustained heat in severe thunderstorms, by the use of infrared detection equipment.

## A SELECTED BIBLIOGRAPHY


1. Jones, H. L. "The Identification of Lightning Discharges by Sferics Characteristics." Recent Advances in Atmospheric Electricity. ed. L. G. Smith, New York: London: Paris: Los Angeles: Pergamon Press, 1958, 543-56.

2. Vonnegut, B. Electrical Theory of Tornadoes. (Report to Office of Naval Research). Cambridge: Arthur D. Little, Inc., 1956.

3. Landshoff, R. K. Magnetohydrodynamics. Stanford: Standard University Press, 1957, p. 3.

4. Cobine, J. D. Gaseous Conductors. New York: Dover Publications, Inc., Second Edition, 1958.

5. Alfven, H. Cosmical Electrodynamics. London: Oxford at the Clarendon Press, 1950.

6. Bostick, W. H. and M. A. Levine, "Demonstration in the Laboratory of the Existence of Magnetohydrodynamic Waves in Ionized Helium." Physical Review, Vol. 87, No. 4, Letters to the Editor (June 6, 1952), 671.

7. Dow, W. G. Fundamentals of Engineering Electronics. New York: John Wiley & Sons, Inc., 1937.

8. Byers, H. R. Thunderstorm Electricity. Chicago: The University of Chicago Press, 1953.

9. Thornton, W. M. "On Thunderbolts." Philosophical Magazine and Journal of Science, (May, 1911), p. 630.

10. Ritchie, D. J. "Reds May Use Lightning as Weapon." Missiles and Rockets, Vol. 5, No. 35 (August 24, 1959), 13-14.

11. Rosenbluth, M. "Dynamics of a Pinched Gas." Magnetohydrodynamics. ed. R. K. Landshoff, Stanford: Stanford University Press, 1957, 57-66.

12. Jones, H. L. Research on Tornado Identification. (First Quarterly Progress Report to U. S. Army Signal Corps), Stillwater: Oklahoma State University Press, 1955.

13. Jones, H. L. and Philip Hess. "Identification of Tornadoes by Observation of Waveform Atmospherics." Proceedings of Institute of Radio Engineers, Vol. 40, No. 9, (1952), 1049-52.

14. Bostick, W. H. "Plasmoids." Scientific American, Vol. 197, No. 4, (October, 1957), 87-94.

15. Bostick, W. H. "Experimental Study of Plasmoids." Physical Review, Vol. 106, No. 3 (May 1, 1957), 404-12.

16. Bostick, W. H. "Experimental Study of Ionized Matter Projected Across a Magnetic Field." Physical Review, Vol. 104, No. 2 (October 15, 1956), 292-99.

17. Flora, S. D. Tornadoes of the United States. Norman: University of Oklahoma Press, 1953.

18. Vonnegut, B. and C. B. Moore. "Giant Electrical Storms." Recent Advances in Atmospheric Electricity. ed. L. G. Smith, New York: London: Paris: Los Angeles: Pergamon Press, 1958, 399-410.

19. Humphreys, W. J. Ways of the Weather. Lancaster, Pennsylvania: Jaques Cattell Press, 1942, 243-44.

20. Schonland, B. F. J. The Flight of Thunderbolts. London: Oxford at the Clarendon Press, 1950.

21. Dauvillier, A. "Ball Lightning and Thermonuclear Reactions." Compte Rendus. No. 25 (December 16, 1957), Atmospheric Electricity, (March 3, 1959), p. 2155.

22. Flint, H. T. "Ball Lightning." Journal of Royal Meteorological Society, Vol. 65 (October, 1939), 532-35.

23. Johnson, John C. Physical Meteorology. Cambridge: New York: Technology Press of M. I. T., John Wiley & Sons, Inc., 1954.

24. Benedicks, C. "Theory of the Lightning Ball and its Application to the Atmospheric Phenomenon Called 'Flying Saucers'." Arkiv Geofysik, Paper 1, 1952, 1-11.

25. Bishop, A. S. Project Sherwood. Reading, Massachusetts: Addison-Wesley Publishing Company, Inc., 1958.

26. Karr, H. J. "Experimental Studies of the Pinch Effect." The Plasma in a Magnetic Field. ed. R. K. Landshoff, Stanford: Stanford University Press, 1958, 40-59.

27. Farkas, A. Light and Heavy Hydrogen. London: Cambridge University Press, 1935, 118-41.

28. Fleming, J. A. Terrestrial Magnetism and Electricity. New York: Dover Publications, 1949.

29. Schonland, B. F. J. Atmospheric Electricity. London: Methuen and Company, Second Edition, 1953.

30. Loeb, L. B. "The Positive Streamer Spark in Air in Relation to the Lightning Stroke." Atmospheric Explorations, ed. H. G. Houghton, Cambridge, New York, London: The Technology Press of M. I. T., John Wiley & Sons, Inc., Chapman & Hall, Ltd., 1958, 46-75.

31. Roemer, E. A. Correlation of Lightning Strokes with Their Sferic Recordings. Unpublished Masters dissertation, Oklahoma State University, May, 1958.

32. Boudreaux, Felix. A Study of the Quasi-static Electric Fields of Severe Thunderstorms. Unpublished Ph.D. dissertation, Oklahoma State University, August, 1959.

33. Kelly, R. D. Development of Electronic Equipment for Tornado Detection and Tracking. Unpublished Ph.D. dissertation, Oklahoma State University, 1957.

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