The Electrification of Precipitation and Thunderstorms*

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The following paper is one of a planned series of invited papers, in which men of recognized standing will review recent developments in, and the present status of, various fields in which noteworthy progress has been made.—*The Editor*

Summary—**The fundamental physical processes responsible for the observed electrification of ordinary precipitating clouds, as well as thunderstorms, is considered in quantitative terms and new facts are emphasized. Cosmic rays and radioactivity, sometimes supplemented by corona and photoionization, produce ion pairs in the atmosphere. These ions are transferred to cloud droplets or ice crystals by diffusion or by electric fields and thereby establish a droplet charge distribution. This distribution is profoundly influenced by the observed differences between the positive and negative light ion conductivities in the atmosphere. Electrification by induction frequently supplements these processes. Rain formed by the association of these cloud elements may be highly electrified and a mixture of positive and negative drops is usually produced. Experimentally well-established processes are considered that can selectively charge such rain or selectively discharge it. It is shown that either process can establish a free space charge distribution that is transferred toward the ground by gravity, and may be large enough to develop electric fields exceeding the dielectric strength of air. Lightning then intervenes. The conditions necessary to establish gross free charge distributions by regeneration are specified and shown to be met under frequently occurring meteorological situations. Many of the observed characteristics of thunderstorms are traceable to the nonuniform semiconducting nature of the lower atmosphere and its nonohmic behavior. The analysis reflects the results of earlier work.**

Introduction

The instantaneous release of some hundreds of kilowatt hours of electrical energy by a lightning discharge is one of nature's most awesome spectacles. Although the lightning discharge has excited the wonder of many men, the complexities of weather processes have obscured the fundamental electromechanics and delayed the collection of data necessary to illuminate the basic physical processes. Urgently required data on the distribution of free electric charge within a thundercloud are still missing, although flights through some 25 active thunderstorms by the highly instrumented laboratory aircraft of the Army-Navy Precipitation Static Project [11] have provided a number of highly valuable samples. These samples may not represent all the thunderstorms distributed over the world and in too many cases the measurements are contradictory. This writer is sensitive to the fact that the observations are still incomplete and not always consistent or accurate, but our critics may notice that flying in active thunderstorms is somewhat hazardous and that our small store of data was obtained only after the highly instrumented project airplanes had been intentionally flown through some 25 active thunderstorms and been struck by lightning three times! The author, accordingly, bequeaths to an unsympathetic critic the job of collecting many more facts. We trust that he will be lucky.

The object of the present review is to bring together the presently available and reliable physical data on thunderstorms and attempt to synthesize from them as complete a quantitative description of the electrified thundercloud as these data permit. The principal problem of thunderstorm electricity is to describe those processes responsible for establishing the over-all free charge distribution just before lightning is initiated. The physics of the actual discharge is simple in concept, but its detailed description is complex. A discussion of its characteristics, therefore, are reserved for separate analysis.

The electrostatic state established inside a thundercloud by meteorological processes can usually be represented by a steady state. Accordingly, if one had a complete space-wide description of the electrostatic potential, electric field, or free space charge at any given instant, he could immediately calculate most of the required physical quantities. Actually, such data are far beyond the reach of present measurement techniques and one must be content with samples of the above quantities and use these as a framework to support a consistent quantitative description. In general, the potential differences cannot be measured and our knowledge of the electrostatic state is based primarily upon electric field measurements, and the charges carried toward the ground on the precipitation particles inside active thunderstorms. Valuable clues to the basic processes can be inferred from the measured charges deposited on the earth by rain.

An improved understanding of the fundamental processes has resulted from the invention and development of new instruments for measuring the electrical state and the important physical characteristics of falling rain. The development of adequate instruments has absorbed much of the writer's effort but their description will be found elsewhere [14, 15, 21, 42]. It is sufficient to notice that out of the instrument development program has emerged electric field meters capable of

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operating continuously in very heavy rain both on the ground and on aircraft. These instruments measure continuously both the sign and magnitude of the electric field and have a response time of about one second. Such data are of the utmost importance in assessing thunderstorm electrification processes.

Supplementing the above have been instruments which permit the determination of the sign and magnitude of the free charge carried on falling rain. It is sometimes possible to measure simultaneously the mass of the drop by means of an instrument which has been particularly valuable on aircraft in providing specific information on the drop charges and their approximate distribution. Other devices, such as a small wind tunnel employing ionized air as the moving fluid, have been of great value in the laboratory. Descriptions of some of the above instruments will be found in the Bibliography [14, 15, 21, 42].

As a direct result of efforts to develop new and better instruments, we have the largest store of coherent measurements yet made in the field of atmospheric electricity; their availability is reflected in the conclusions and references cited herein. The emphasis in the present review has been largely determined by these measured data. Theoretical estimates have been invoked primarily to bridge some of the present gaps in the measurements and to guide the interpretation.

The common active thunderstorm is a veritable museum of atmospheric phenomena. Clouds, heavy rain, snow, and hail are commonly produced and intermixed in a typical active storm and the whole matrix is bathed in turbulence and vertical air currents of great complexity. It is inevitable, therefore, that the electrical phenomena will be extremely difficult to interpret and describe in quantitative terms. Thunderstorms commonly develop in thermally disturbed air masses during the summer months or whenever large amounts of water vapor are present in the atmosphere. The typical summer thunderstorm is approximately 20 kilometers in diameter, although the cloud mass itself may be somewhat more extensive. It commonly extends vertically about 12 km but occasionally may develop to 15 km with an increased probability for the production of hail. The complexity of typical thunderstorms suggests that many processes contribute to the observed state [1, 10, 47] and therefore, it is particularly necessary to separate those that are most energetic for quantitative discussion. These selections will doubtless lead to differences of opinion but as long as one clings steadfastly to the observed data, these differences need not be serious.

Characteristics of Active Thunderstorms as Observed on the Ground

As far as this writer is aware, normal lightning activity has never been observed in clear air *except in the vicinity* of falling precipitation. There is much additional evidence showing that the principal electrical effects accompanying a thunderstorm are closely related to the production and fall of precipitation. Precipitation is necessary but is not always sufficient to induce visible electrical activity. The free electrical charges brought to the earth by rain may vary over a wide range; it has been observed that electrical activity may be produced even with moderate precipitation. Conversely, heavy precipitation like that frequently encountered in a mature hurricane sometimes develops surprisingly little lightning activity. The connection between precipitation and lightning activity, therefore, is not a direct one.

The Electrification and Energetics

The electrification observed in thunderstorms implies the gross separation of free electrical charge with a consequent expenditure of large amounts of energy. It is important to understand this process. The electrification is usually established by a three-stage mechanism whereby positive and negative ions are first generated from neutral molecules by cosmic rays and radioactivity, or in special cases by corona or photoelectric effects. The ions are transferred to cloud droplets by diffusion and conduction. The cloud droplets, in turn, unite to form a mixture of positively and negatively electrified raindrops. The rain is then selectively electrified to permit a final gross separation of positive and negative charge. Under special conditions, charge is separated by the more efficient processes of induction.

Cosmic rays produce about 10 ion pairs per cubic centimeter per second in the lower atmosphere and this increases, more or less uniformly, to 45 at an altitude of about 14 km. Extensive measurements show that when cloud droplets are present, the ions produced by cosmic rays normally diffuse onto the cloud droplets to establish an equilibrium charge. For a typical cloud containing 400 droplets per cubic centimeter, all having a radius of 6 microns, it is found that the droplets in every cubic kilometer of cloud normally accumulate a total charge of the order of one coulomb. Cosmic rays will separate this much charge in about five minutes. The above clouds are nearly neutral and half of the droplets carry positive charges while the other half carry negative charges. These two first stages of thunderstorm electrification are perfectly clear and capable of quantitative formulation. However, when the cloud droplets grow into raindrops and these fall in the atmosphere in the presence of electric fields, the electrical processes become enormously complex. Many data are available describing the probable subsequent course of events and these will be considered in later sections.

The energy necessary to separate the free charges carried by the raindrops is derived from gravitational forces and it is necessary to show that they are adequate. The electric field throughout a typical thunderstorm is frequently observed to be about 150 volt/cm or 0.5 statvolt/cm, although fields 20 times this are known to occur [12]. The energy density required to establish the field is $(\frac{1}{8}\pi)E^2$ erg/cm^3 so that at a given instant the total electrostatic energy W of the storm is

$$W = \frac{1}{8\pi}\int E^2 dU = 10^{-2}U = 2 \times 10^{16} \text{ erg}$$
$$= 550 \text{ kilowatt hours,} \tag{1}$$

where dU is the element of volume U. In a typical storm this volume approaches 2×10^{18} cm^3. Perhaps most of this calculated energy is expended in a single lightning stroke whose energy is specified by the product of the effective potential and the transferred quantity of electricity. Therefore, because we will show presently that a typical stroke neutralizes some 17 coulombs, one may estimate that the initial cloud potential *exceeds* 10^8 volts. It is not surprising, therefore, that lightning sparks 5 to 10 km long are frequently produced in the free atmosphere.

Consider a precipitating thundercloud in which the liquid or crystalline water content (LWC) is a representative 10^{-6}gm/cm^3. The work that the free water in this unit volume can do in falling towards the ground a distance h is (LWC) gh. where g is the acceleration due to gravity. This energy must necessarily exceed the electrostatic energy stored in the same unit volume or $(1/8\pi)E^2$. Thus, if E approximates 0.5 statvolt/cm the electrostatic energy may be derived from the available condensed water falling a distance of only 10 cm. Since raindrops normally fall many kilometers, the available gravitational energy is thousands of times more than that necessary to establish a typical electric field. Therefore, fairly inefficient electrical processes are entirely capable of describing a common thunderstorm. It is worthy of note in passing that the free water transferred to the high levels in the atmosphere ultimately derives its energy from the sun which originally evaporated the water from the earth.

It is clear that the precipitation must always be electrified if active lightning is to be produced. Many suggestions have been made as to the basic electrification processes [4, 10, 22, 24, 36, 47]. Perhaps most processes invoke the transfer of ions to the drops by diffusion, by conduction, or by differential convection. Others, of a more energetic type, such as direct induction or selective conduction induced by polarization, play an important role. Still others attributing the charge to systematically oriented surface layers have their special advocates. Irrespective of the particular process, the charges on raindrops may be greatly enhanced whenever large numbers of electrified droplets associate to form larger raindrops [24, 25, 32].

Electric Field

Perhaps the most important index of thunderstorm activity is the electric field measured both at the ground and inside the active cloud high above. A vertically upward surface electric field corresponding to a positive surface charge is adopted as positive. This is the definition used by physicists and mathematicians and is opposite in sign to that used by a number of workers in atmospheric electricity. In fair weather the surface electric field intensity is negative and approximates -1.5 volt/cm. The development of clouds over a given observing station usually has little influence on the fair weather field until 10 or 20 minutes before precipitation is observed at the ground. The electrification of the droplets permits a selective electrification of the cloud as a whole that thereby produces measurable electric fields at the surface. In a typical stable cloud the electric field is less than 10 volt/cm and probably less than 1 volt/cm. When the cloud becomes unstable and produces slight precipitation, the electric field measured on the ground commonly approximates $+10$ to $+25$ volt/cm and may fluctuate or even reverse sign. Frequently this electric field is quite steady and as the precipitation rate or vertical convection within the cloud increases, the electric field may increase to ± 50 or more volts per centimeter at which time discontinuities in the electric field are sometimes observed [13]. These discontinuities normally accompany a lightning or invisible static discharge. In the presence of sufficient cloud instability and vertical convection, a typical thunderstorm is produced and the electric field at the ground may then increase to about ± 100 volt/cm with maxima up to ± 140 volt/cm. Marked discontinuities in the field are observed at the instant of nearly every lightning discharge and reversals of sign are common. In an active storm the electric field may be either positive or negative but the basic charging processes, once the thunderstorm is well started, are such as to produce predominantly positive electric fields at the earth's surface.

A network of eight electric field meters was installed in Kansas during the thunderstorm season of 1955. We have complete records of the electric field established at these stations by an active thunderstorm throughout a three-hour period just prior to and after a disastrous tornado passed through Udall, Kan. One station within a mile or two of the funnel lost the door of the barn in which it was housed. Excerpts from these records are given in [30] and in Fig. 1. Their analysis shows that, in general, the electric field may be built towards negative electric field values for the first and last 10 to 20-minute period as shown in Fig. 1, part 3. During the *main part* of the thunderstorm, however, the electric field is positive 61 per cent of the time but *builds towards positive* electric fields more than 90 per cent of the time as in Fig. 1, part 1, and Fig. 1, part 2. Such a field implies that an excess negative charge systematically accumulates in the clouds overhead. The main problem of thunderstorm electricity is to describe the processes whereby this charge and the associated electric field are produced and show how to calculate their magnitude.

In the above thunderstorm, the measurements show that the electric field *just prior* to the lightning discharge was positive in 88 per cent of some 2600 events. Moreover, the electric field immediately after the discharge was negative in 65 per cent of the cases. This implies, and the records clearly show, that the typical lightning discharge not only neutralizes the free charges accumu-

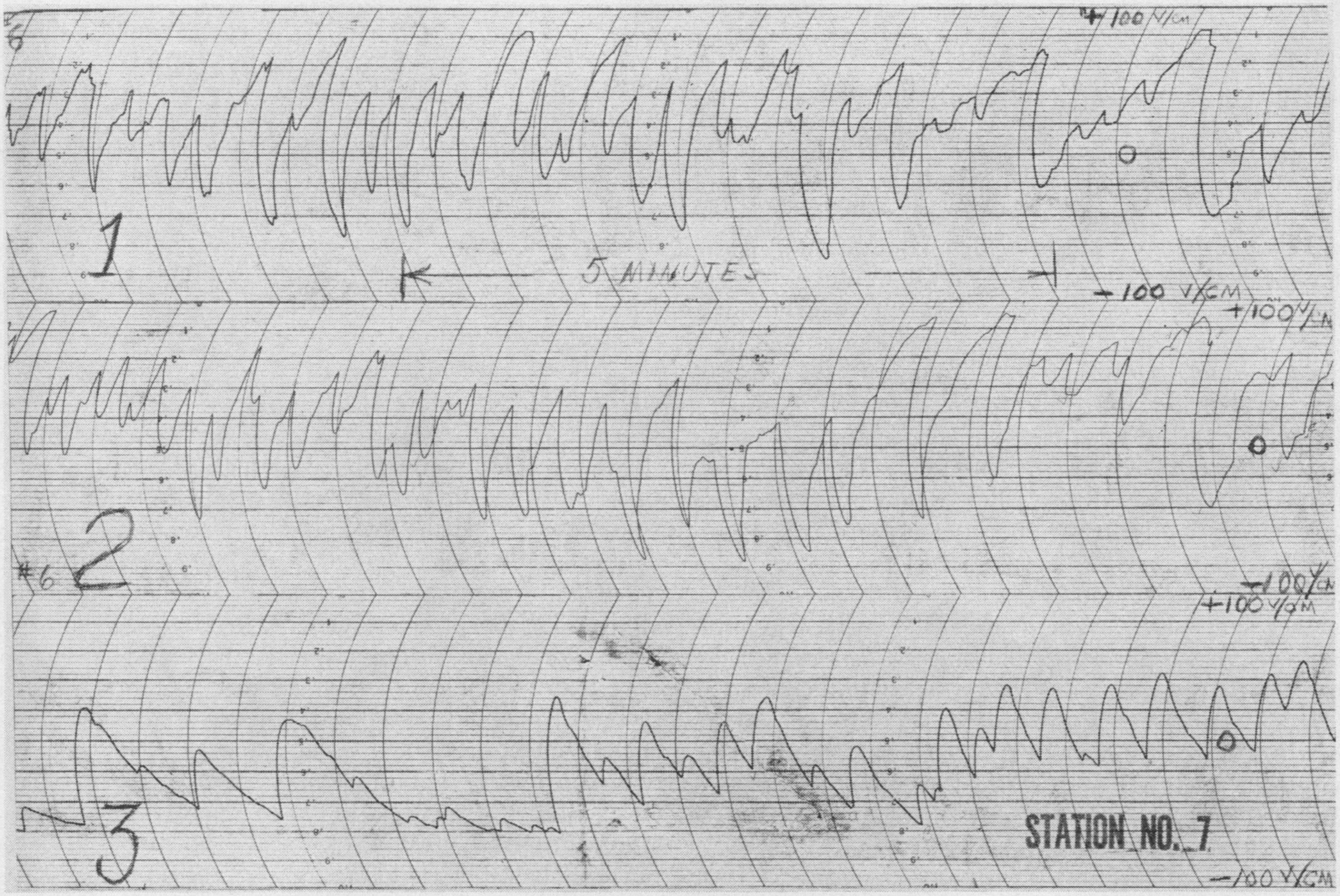

Fig. 1—Extracts from electric field intensity records measured at ground. Active Kansas thunderstorm, May 25, 1955. Electric fields in two top records build toward positive fields. The lower record builds toward negative fields. The measured discontinuities are always accompanied by a lightning discharge.

lated overhead but, in the majority of cases, apparently overneutralizes the charge and develops an electric field which is usually of opposite sign to that existing prior to the lightning stroke. To be more specific, it is found that the average electric field is this active Kansas thunderstorm just prior to a lightning discharge was +41 volt/cm and after the discharge was −10.4 volt/cm. The number of discharges, wherein negative charge was neutralized overhead, was more than 10 times the number of events when positive charge was neutralized, and the average measured *change* of electric field was −50.2 volt/cm or 0.16 statvolt/cm. The largest electric field measured by the writer on the ground was +140 volt/cm, which we will see is less than 1/10 of the maximum electric fields commonly measured on aircraft well *inside* an active thundercloud.

The mean charges neutralized by lightning as summarized in the above data may be immediately calculated by noticing that the electric field observing stations were probably only two or three kilometers below the free charge distributions and therefore these may be assumed to approximate a horizontal sheet. Neglecting the fringing near the edges of these clouds one may write that

$$E = 4\pi\sigma = 0.16 \text{ statvolt/cm} \qquad (2)$$

where E is the observed electric field and σ is the free charge per unit area of the cloud. Now if one considers only the change in the electric field, it is clear that the change in σ corresponds to the discharge of the cloud. Now analysis of many thunderstorms shows that a typical storm has dimensions of 20 km×20 km so that by (2) one finds that the average charge neutralized for more than 2600 measurements approximates 17 coulombs. This value is in good agreement with earlier estimates by other investigators.

Further analysis of the same thunderstorm shows that as the thunderstorm increases in intensity the number of lightning strokes per minute steadily increase to an average maximum value of 4.4 strokes per minute. At the particular station closest to the passage of the tornado funnel the lightning rate increased to an average maximum of 7.2 strokes per minute.

The electric fields measured at the top of mountains exhibit generally the same characteristics as the Kansas storm except that the electric fields are commonly much larger. A program of measurements on mountain tops is currently underway and more data will shortly be available. On top of a mountain nearly 6600 feet high, maximum electric fields of more than 1000 volt/cm have been measured.

Raindrop Charges

Important clues as to the fundamental electrical processes inside an active thunderstorm may be discovered by a careful study of the electrical charges brought to the earth by rain. It was found long ago that quietly falling rain is weakly electrified whereas raindrops falling from active thunderstorms are usually highly charged.

Gschwend [8] observed that the charges brought down on typical thunderstorm raindrops were seldom of a single sign and that a mixture of positive and negative charged drops was characteristic of almost all storms. This fact has been verified many times and has an important bearing on the interpretation of thunderstorm phenomena. Gunn and Devin [19] measured and analyzed the characteristics of some 7000 raindrops that represented a continuous sample of the drops falling to the ground from an active thunderstorm. The distribution of the number of drops in relation to the sign and magnitude of the free charge they carried is given in Fig. 2. This shows clearly that save for a slight preference for small positive charges the distribution is nearly symmetrical and does not appreciably depend upon the sign of the surface electric field. The mixture of positive and negative drops usually observed and the independence of drop charge and the sign of the electric field show that the origin of these charges is to be found in mechanisms taking place far above the earth's surface.

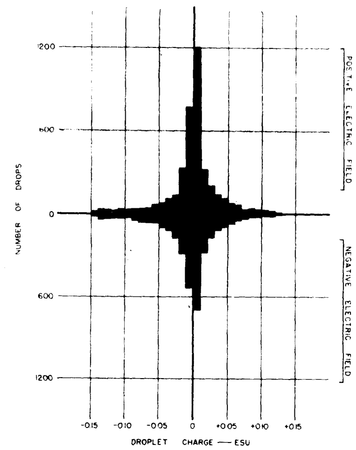

Fig. 2—Number of drops measured at the ground in free charge intervals of 0.01 esu for active thunderstorms of May 5 and June 10, 1950. Total positive charge brought to the ground was 83 per cent of the total negative charge.

Summarizing the data of Fig. 2, it was found that the average charge for positive drops in the above thunderstorm was 0.022 esu/drop and for the negative drops the charge was 0.031 esu/drop. Moreover, the ratio of the sums of all the positive to negative charges brought down on this thunderstorm rain was 0.83. Related sets of data on the charge carried by rain have been given by Scrase [44], by Chalmers and Pasquill [3], and by Banerji and Lele [2]. Average values for raindrop charges are summarized in Table I.

TABLE I

Average Free Electrical Charge on Individual Droplets (ESU$\times 10^3$)

Observer	Altitude (feet)	Charge	Quiet rain	Shower rain	Electrical storm rain	Quiet snowfall	Squall snowfall
Gschwend (1921)	surface	+	0.24	1.75	8.11	0.09	5.64
		−	0.53	5.43	5.88	0.06	4.78
Banerji and Lele (1932)	surface	+		6.4	6.9		
		−		6.7	7.3		
Chalmers and Pasquill (1938)	surface	+	2.2	1.3	3.7*		10.5
		−	3.0	2.3	9.2*		5.7
Gunn (1947)	4000	+		ϕ			
		−		24			
	12,000	+		41			
		−		100			
	20,000	+		63			
		−		ϕ			
Gunn (1949)	surface	+			15	0.67	
		−			19	1.0	
Gunn (1950)	5000	+			81		
		−			63		
	10,000	+			148		
		−			112		
	15,000	+			123		
		−			76		
	20,000	+			52		
		−			62		
Gunn and Devin (1953)	surface	+			22		
		−			31		

* Actual lightning activity doubtful.

ϕ No droplets of this sign were observed at the indicated level.

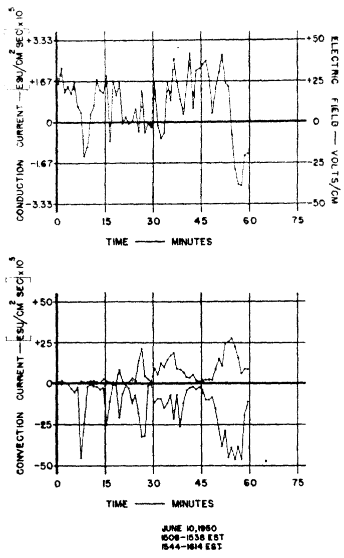

Fig. 3—Top: Electric field and estimated conduction current averaged over one-minute intervals for storm of May 5, 1950 Bottom: The convected current density for positive drops is plotted above the axis. Below the axis is the negative drop current density. The net current density is their sum.

Convected Current Density

When the charges on falling rain are directly measured together with their size and numbers per unit volume it is possible to calculate the convected current density i through

$$i = \sum NQV \tag{3}$$

where N is the number of drops per unit volume, Q is their free charge, and V is their velocity of fall. Since the raindrops all fall towards the ground, the contribution of the positively charged and negatively charged drops are of opposite sign. Accordingly, it is expedient to calculate and plot separately the charge per unit area transferred per unit time to the earth by both the positive and negative drops. Such data [19] are summarized in Fig. 3 and are placed adjacent to simultaneously collected data for the electric field and the presumed conduction current density. The convected current densities for the positive drops are plotted above the axis while those for the negative charges are plotted below. It may be noticed in Fig. 3 that the convected current densities for the positive and negative drops are seldom of the same magnitude and, therefore, rather large fluctuations of the free drop space charge density are generally encountered. These irregularities produce associated fluctuations in the local electric field. Further, since the net convection current density is notably larger than the conduction current of opposite sign, a surplus free charge necessarily accumulates on the ground and this in turn modifies the electric field. One may notice particularly from the observed curve that the excess droplet convected current density is sometimes as much as 4×10^{-4} esu/cm^{2}sec. These direct measurements permit one to infer, through a simple analysis, that the observed electric fields in the free atmosphere can be excited and maintained by the observed charges on falling rain.

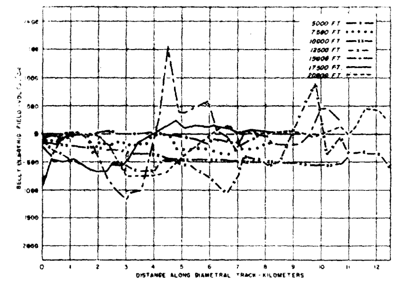

Fig. 4—Electric field intensity measured on belly of B17 airplane during successive passages through active thunderstorm of July 24, 1945 at different levels. Positive fields correspond to positive surface charges at the field meter site.

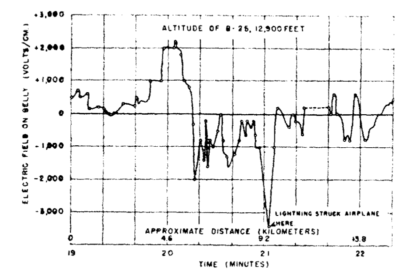

Fig. 5—Electric field intensity at belly of B25 airplane during a lightning strike at 13,000 feet on August 5, 1944.

Electrical Characteristics Measured Inside Active Thunderclouds by Aircraft

Although important guide posts for the development of an adequate description of thunderstorm electricity are established by surface data, yet there are many important facts that can be determined only by flying through active thunderstorms. The highly instrumented airplanes of the Army-Navy Precipitation Static Project, which the writer directed during World War II, intentionally flew through some 25 active thunderstorms and succeeded in collecting valuable data. These measurements still provide the best available cross section of thunderstorm electrification phenomena. Many more data are urgently required. The laboratory airplanes were equipped with induction-type electric field meters, both on the top and bottom of the main cabin. A drop charge apparatus was installed under one wing and simultaneous measurements could be made of the electric fields, drop charges, and other more obvious meteorological factors [11, 12, 17].

Observed Electric Fields

Repeated flights through active thunderstorms showed that the electric field at low levels approaches that commonly measured at the surface and that these fields generally increase to a maximum in the vicinity of the freezing level. Somewhat typical data for a number of passes through the active thunderstorm of July 24, 1945, are summarized in Fig. 4. The measurements show that at altitudes near the freezing level the electric fields frequently exceed a thousand volts per centimeter. In a total of nine thunderstorms examined in 1944 by repeated flights through each, the average measured maximum field was 1300 volt/cm [13]. One flight through an

TABLE II*

Altitude	Temp.	Positive drops		Negative drops		Particle space-charge density		Measured drop density	Mean drop mass for liquid water content of 0.5 gm/m³	$(Q/m)_{est}$	
		Number	Charge	Number	Charge	Positive	Negative			Positive drops	Negative drops
Feet	°C		esu/drop		esu/drop	esu/cm³	esu/cm³	drop/cm³	grams	esu/gm	esu/gm
5,000	+14.7	89	+0.081	171	−0.063	5.6×10^{-5}	3.1×10^{-5}	4.8×10^{-4}	1.0×10^{-3}	81.0	63.0
7,500	+10.3	43	+0.280	47	−0.267	14.5×10^{-5}	15.6×10^{-5}	3.2×10^{-4}	1.5×10^{-3}	185.0	178.0
10,000	+6.7	71	+0.148	133	−0.112	4.9×10^{-5}	2.9×10^{-5}	2.5×10^{-4}	2.0×10^{-3}	74.0	56.0
12,500	+2.4	0	—	196	−0.135	—	7.0×10^{-5}	4.4×10^{-4}	1.1×10^{-3}	—	123.0
15,000	−0.7	130	+0.123	150	−0.077	8.5×10^{-5}	4.8×10^{-5}	5.7×10^{-4}	0.8×10^{-3}	153.0	95.0
17,500	−5.5	45	+0.036	79	−0.041	1.5×10^{-5}	1.6×10^{-5}	4.1×10^{-4}	1.2×10^{-3}	30.0	34.0
20,000	−9.9	76	+0.052	74	−0.062	1.1×10^{-5}	3.6×10^{-5}	3.4×10^{-4}	1.4×10^{-3}	37.0	44.0
									Mean	93.0	85.0

* Summarized data for drops measured inside active thunderstorm of July 24, 1954. The particle space charge densities are estimated from the drop charges actually observed and, therefore, ignore the smaller and possibly more numerous charges carried by the cloud droplets or very small raindrops. The specific charges, or charges per unit mass, are considered rough.

active storm encountered both positive and negative fields of 2000 volt/cm and a half minute later the field increased to 3400 volt/cm at which time the lightning struck the airplane and damaged some of our instruments [12, 13]. The electric field intensity throughout this interval is shown in Fig. 5. All aircraft electric field measurements are subject to a possible correction of the order of unity because of the unknown orientation of the electric field in relation to that of the aircraft. It is a significant observed fact that 65 per cent of all lightning strikes to operating aircraft occur at outside air temperatures within the narrow range of from 0° to +5°C. Although air traffic at these levels is high, the facts still suggest that the layer of maximum electrical activity can hardly exceed a thickness of 2 or 3 km.

One characteristic of the electric field distribution in thunderstorms is worthy of emphasis. The free charge in the thundercloud is distributed over a large volume and it was originally anticipated that the electric fields would gradually build up as the thundercloud was approached. Actually it was found that the electric field outside the cloud approximated only 150 to 200 volt/cm in the clear air even through the towering cumulus overhead suggested that one was very close to the electrically active centers.

However, just as soon as the aircraft entered the cloud, the electric fields increased rather rapidly and in a matter of 15 seconds the field might increase to ±1000 volt/cm. Inside the cloud large values of field, both positive and negative, were commonly encountered, although the geometrical position of the aircraft in relation to the active center of the thundercloud had changed very little [11, 17]. This observed fact emphasizes the importance of space charge layers near the boundary of thunderclouds. The important role of such layers will be discussed in another section.

Observed Raindrop Electrification

The raindrops inside an active thunderstorm are highly electrified. The writer pointed out long ago that the measured charges were frequently so large that the electric field at the surface of the drop might approach the dielectric strength of air [14]. This implies that increased charges on the larger drops might initiate corona discharge and thus limit the electrification [14]. The measured electric charges in an active Minnesota thunderstorm are summarized in Table II (above) and show clearly that not only are the electric fields a maximum near the freezing level but the drop charges also. Table II gives not only the measured values of the drop charges, but also a rough estimate of the specific charge or charge per unit mass. A plot of the average free charge carried by the precipitation particles at different positions within the thundercloud at a given level is given in Fig. 6. Many more data of this nature may be found [17]. It is observed that frequently a mixture of positive and negative drops exists but occasionally regions 1 or 2 km in linear dimension contain raindrops of *only a single sign* [17]. This statement applies only to the measured drops and does not imply that there may not be relatively large numbers of much smaller cloud droplets carrying charges of opposite sign. It is clear, however, that these large rapidly falling drops are primarily responsible for the convective transport of free charge towards the ground by gravitational action and are, indeed, the active agents in separating the free charge within the cloud.

The available data on the electricity transferred to the earth by rain show that the charges are overwhelmingly positive for very light rain and low precipitation rates. But, this decreases with increasing precipitation until in almost all thunderstorms the free charge brought to the ground is predominantly negative [44]. These data probably imply that raindrops become more negative at higher levels and, indeed, this is just what is measured in aircraft flights both in the mild cold front and in thunderstorms which show that at rain-forming levels the total negative charge on the rain is some 60 per cent larger than the total positive charge [12, 17]. This excess may be directly attributed to the differential discharge resulting from the observed differences in the positive and negative light ion conductivities at flight altitudes or to the selective electrification of cloud droplets when $\lambda_+ \neq \lambda_-$.

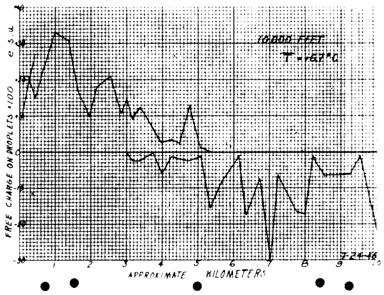

Fig. 6—Measured free charges carried by individual raindrops at various positions inside thunderstorm of July 24, 1945. This curve for 10,000 feet. For additional data, see Gunn [17].

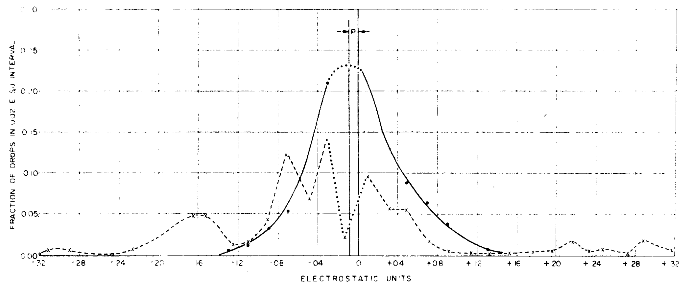

Fig. 7—Distribution of fractional numbers of charged drops in 0.02-esu intervals. Solid curve for mild cold front of July 27, 1945. Dashed curve for active thunderstorm of July 24, 1945. The dotted sections imply that weakly charged drops may have been missed.

Comparison of Electrification Inside an Active Thunderstorm with that Observed in a Mild Cold Front

It is of considerable interest to compare the electrical properties of heavy precipitation produced within a mild cold front with those observed inside an active thunderstorm. The laboratory airplane flew through a mild cold front that crossed Minnesota on July 27, 1945. Precipitation was moderate to heavy; no lightning activity was observed. The charges measured on the individual raindrops falling at various levels are summarized in Table III (opposite). A comparison with the thunderstorm data of Table II shows that the measured drop charges on the rain within the cold front were roughly one half of the charge measured on the drops falling within the active thunderstorm. The charges on the raindrops at all levels gave a nearly smooth distribution like that of the solid curve in Fig. 7. This distribution was nearly symmetrical about the axis of zero charge and was roughly Gaussian. On the other hand, the distribution of charges in the thunderstorm suggested great complexity and there were large numbers of drops carrying both positive and negative charges of considerable magnitude, as shown in the dashed curve of Fig. 7. At any given level the data were insufficient to provide representative statistical data, but did show that in both types of storm large volumes sometimes existed wherein the charge on the larger precipitation particles is *all of one sign*. The data of Tables I and III permit one to estimate the total free charge carried by all the rain drops if they are assumed to be distributed uniformly over a sphere of radius 1 km. One may verify that if the charges are all of one sign, electric fields over the surface of the assumed sphere are great enough to initiate lightning discharges that are not observed. Thus, the summarized data show that charges of opposite sign, presumably on the smaller cloud droplets or the air, are usually intermixed with the charges measured on the large raindrops and that only a partial separation of the measured charges is necessary to establish active lightning. One concludes from a comparison of the thunderstorm and mild cold front regimes that heavily precipitating regions exhibiting modest measured electric fields are intrinsically capable of establishing a charge distribution adequate to produce lightning, and that the differences between a mild cold front and a thunderstorm are probably related principally to the selective separation of charges already present on the rain. These seemingly minor differences between the thunderstorm and nonthunderstorm regimes must be objectively considered in formulating a quantitative description of thunderstorm phenomena.

Electrical Properties of the Semiconducting Lower Atmosphere

The earth's lower atmosphere is essentially a high grade insulator in which ion pairs are continuously formed principally by cosmic rays and radioactivity. Because of the decrease in density of the atmosphere with increasing altitude and because most of the radioactive material is concentrated near the surface, the produced ionization changes markedly with altitude. In addition to the observed variation of ionic density, the ionic mobility regularly increases with altitude, and is somewhat greater for the negative ion than for the positive ion.

The number of ions per unit volume established in the atmosphere at equilibrium depends not only upon the rate of ion production but also upon their rate of disappearance. In clean air the rate of disappearance is determined by the recombination coefficient; but, in ordinary air containing various types of pollution and cloud droplets, the rate of disappearance is determined by a number of factors that have been discussed adequately in earlier communications [22, 23, 31].

The most important factors controlling the electrical state of the atmosphere are the electrical conductivities for the positive and negative light ions and their ratio. By ignoring a number of secondary processes which may be important under special conditions, one may summarize present views regarding the atmospheric conductivity under two headings.

Clean Air Conductivity

In the absence of suspended particulate matter the rate of recombination of the positive and negative ions is given by

TABLE III*

Altitude	Temp.	Positive drops		Negative drops		Particle space charge density		Measured drop density	Mean drop mass for liquid water content of 0.5 gm/m³	$(Q/m)_{est.}$	
		Number	Charge	Number	Charge	Positive	Negative			Positive drops	Negative drops
Feet	°C		esu/drop		esu/drop	esu/cm³	esu/cm³	drop/cm³	grams	esu/gm	esu/gm
4000	+12.0	—	—	72	−0.029	—	-0.9×10^{-5}	2.7×10^{-4}	1.8×10^{-3}	—	−16
6000	+ 8.5	—	—	59	−0.027	—	-0.6×10^{-5}	2.2×10^{-4}	2.2×10^{-3}	—	−12
8000	+ 6.0	—	—	157	−0.033	—	-1.3×10^{-5}	4.4×10^{-4}	1.1×10^{-3}	—	−29
10,000	+ 3.0	—	—	78	−0.032	—	-1.0×10^{-5}	2.9×10^{-4}	1.7×10^{-3}	—	−18
12,000	0.0	84	+0.042	130	−0.100	$+1.0\times10^{-5}$	-4.6×10^{-5}	7.5×10^{-4}	0.65×10^{-3}	+64	−150
14,000	− 1.0	8	+0.037	171	−0.037	$+0.15\times10^{-5}$	-1.5×10^{-5}	4.1×10^{-4}	1.2×10^{-3}	+31	−31
16,000	− 4.5	—	—	120	−0.034	—	-1.3×10^{-5}	3.8×10^{-4}	1.3×10^{-3}	—	−26
18,000	− 7.1	200	+0.051	12	−0.032	$+2.2\times10^{-5}$	-0.1×10^{-5}	6.6×10^{-4}	0.76×10^{-3}	+67	−42
20,000	−11.0	129	+0.067	—	—	$+2.7\times10^{-5}$	—	5.1×10^{-4}	1.0×10^{-3}	+67	—
22,000	−15.5	80	+0.037	—	—	$+1.1\times10^{-5}$	—	3.1×10^{-4}	1.6×10^{-3}	+23	—
24,000	—	—	—	—	—	—	—	—	—	—	—
26,000	−23	18	+0.028	—	—	$+0.3\times10^{-5}$	—	1.2×10^{-4}	4.2×10^{-3}	+ 7	—
									Mean	43	40

* Summarized data for drops measured inside mild cold front of July 27, 1945. The particle space charge densities are estimated from the drop charges actually observed and therefore ignores the smaller and possibly more numerous charges carried by the cloud droplets or on the small raindrops. The specific charges, or the charges per unit mass are considered rough.

$$-\frac{dn_+}{dt} = \alpha n_+ n_- = -\frac{dn_-}{dt} \tag{4}$$

where n is the number of ions per unit volume and the subscript denotes their sign, e is the elementary ionic charge, and α is the recombination coefficient. Now if q ion pairs per unit volume per unit time are produced, then the equilibrium electrical conductivities for the positive ions λ_+ and for the negative ions λ_- become

$$\lambda_\pm = \left[\frac{q}{\alpha}\right]^{1/2} eu_\pm \tag{5}$$

where u is the mobility of the appropriate ion and λ is defined by

$$\lambda = \lambda_+ + \lambda_- = \left[\frac{q}{\alpha}\right]^{1/2} e(u_+ + u_-) \tag{6}$$

so that the ratio of the conductivities is

$$\frac{\lambda_+}{\lambda_-} = \frac{u_+}{u_-} \doteqdot 0.8 \tag{7}$$

These expressions are, in general, not applicable near the earth's surface but are somewhat descriptive of the conductivities between 3 and 20 km.

Cloudy or Polluted Air Conductivity

Whenever cloud droplets or other suspended nuclei are present in the atmosphere the positive and negative ions not only recombine with each other but are also transferred to the pollution particles or cloud droplets by diffusion. The droplets thereby develop an equilibrium charge which systematically modifies the diffusion of other ions onto the particle and in this way the ionic density of the mobile conducting ions in the air proper is controlled [41]. The rate of combination of positive and negative ions with the suspended particles of mean population density N_0 and radius a is given approximately by [22]:

$$-\frac{dn_+}{dt} = \frac{4\pi akTu_+n_+N_0}{e\left[1 + \frac{Qe}{2akT} + \cdots\right]} = \frac{4\pi akTu_+n_+N_0}{e\left[1 + \frac{1}{2}\ln\frac{\lambda_+}{\lambda_-} + \cdots\right]} \tag{8}$$

and

$$-\frac{dn_-}{dt} = \frac{4\pi akTu_-n_-N_0}{e\left[1 - \frac{Qe}{2akT} + \cdots\right]} = \frac{4\pi akTu_-n_-N_0}{e\left[1 - \frac{1}{2}\ln\frac{\lambda_+}{\lambda_-} + \cdots\right]} \tag{9}$$

where k is the Boltzmann constant, T is the absolute temperature, and Q is the average charge carried by each droplet. When the number of suspended particles per unit volume corresponds to typical clouds the disappearence of ions by diffusion is much larger than by recombination. In this case, one may equate the rate of disappearance to the rate of production and thus calculate the conductivity due to the light ions moving within the cloud droplet space. The conductivity is then nearly the same for positive and negative ions and is much less than in clear air as suggested by (6). Carrying out the substitution it is found for stable clouds that

$$\lambda = \lambda_+ + \lambda_- = n_+u_+e + n_-u_-e = \frac{qe^2}{2\pi akTN_0}\left[1 + \frac{1}{6}\left(\frac{Qe}{akT}\right)^2 + \cdots\right]. \tag{10}$$

Unless N_0 is very large or very small it is necessary to combine the effects of ionic recombination and ion disappearance by diffusion onto the suspended particulate matter. This has been found possible, although awkward, because the ratio of the positive and negative light ion conductivities measures the particulate matter suspended in the air and this ratio can be estimated from $N_0^2a^2/q$, as shown in Fig. 15. Thus by the aid of this curve and expressions in [31], one may estimate the conductivities for any specified atmosphere.

Accordingly it is clear that while the conductivity of the atmosphere is largely determined by the rate of ion production by cosmic rays, radioactivity, and in some cases by corona or photoionization, the cleanliness of the air plays a major role in determining the measured values and their ratio.

Observed Electrical Conductivity and the Altitude

The electrical conductivity of the lower atmosphere has been measured by many investigators and is known to increase notably with increasing altitude. Gish and Wait [7] have measured the positive and negative light ion conductivities to an altitude of 40,000 feet using aircraft, and found that the positive light ion conductivity was represented by

$$\lambda_+ = 1.5 \times 10^{-4}[1 + 0.13 \times 10^{-10}Z^2]\text{esu}. \quad (11)$$

Moreover, the negative conductivity is given by

$$\lambda_- = 0.4 \times 10^{-4}[1 + 0.42 \times 10^{-10}Z^2]\text{esu} \quad (12)$$

where Z is the altitude in centimeters.

Extensive new measurements at this laboratory extending up to altitudes of 20 km, show that the positive and negative conductivities are generally different. At low levels the positive conductivity is normally in excess and at the "crossover point" the conductivities are equal but above this point the negative conductivity is in excess. The "crossover point" according to (11) and (12) is at 7 km, but our measurements show that it frequently is as low as 3 or 4 km, the exact level depending in an important way upon the cleanliness of the lower atmosphere. We have found that the conductivity λ at an altitude Z may be represented by an improved expression of the form $\lambda = \lambda_0 \exp [fZ - gZ^2]$ where the constants f, g, and λ_0 are considerably different for positive and negative ions. The new measurements and the magnitude of the controlling constants will be reported elsewhere by Woessner and Cobb. Their results clearly show that at a level above 3 or 6 km the conductivity due to the negative ions is considerably larger than that due to the positive ions.

The author is persuaded that these observed differences in the conductivities are an important and controlling factor in determining many basic features of the free charge distribution in the atmosphere.

Discharge of Electrified Clouds and Raindrops

Consider any closed surface in the free atmosphere which contains within its boundaries a total free charge Q. If the distribution of the conductivity λ over the surface is known, one may write that the time rate of charge decay is

$$-\frac{dQ}{dt} = \int E\lambda dS \quad (13)$$

where the integration is carried out over the entire surface. Now if λ is nearly constant over the boundary, it may be placed outside of the integral sign so that one may, by the use of Gauss' law, integrate the equation to show that [10]

$$Q = Q_0 \exp [-4\pi\lambda t] \quad (14)$$

where Q_0 is the initial free charge. This expression is quite general and shows that any free charge is dissipated logarithmically and that it degrades to $1/\epsilon$ in a time known as the *relaxation time* or

$$\tau = \frac{1}{4\pi\lambda}\cdot \quad (15)$$

Since the conductivity of air increases rapidly with altitude, it is evident that the *time to discharge clouds at high level is notably less* than the time to discharge clouds located *nearer the earth's surface.* This effect plays an important role in converting double layer distributions of free charge into unipolar distributions much like those frequently observed [10]. Fig. 8 gives a plot of the total conductivity and relaxation times for free charges located at various altitudes in the atmosphere.

It may be noticed from (13) that the rate of discharge depends on the conductivity over the surface where the electric field is measured. Because the atmosphere is, in general, a poor conductor and because the electric fields established in it by thunderclouds are frequently quite large, there is a marked tendency for ions, of a sign opposite to that enclosed by the surface, to accumulate at the surface while ions of the same sign are repelled. Thus, a space charge layer of considerable magnitude may surround the free charge and notably modify the conductivity of the surface region. The rate at which a cloud discharges, therefore, usually depends somewhat on the sign of the charge.

The accumulation of space charge in the semiconducting atmosphere depends both on the electric field and the local conductivity. To emphasize this fact consider the vertical conduction current flowing through a prism extending from the earth to the ionosphere. When a steady state is established, the current density i in the column is a constant. Accordingly,

$$i = \lambda E = \text{constant} \quad (16)$$

where E is the vertical electric field intensity and λ is the conductivity. If this expression is differentiated

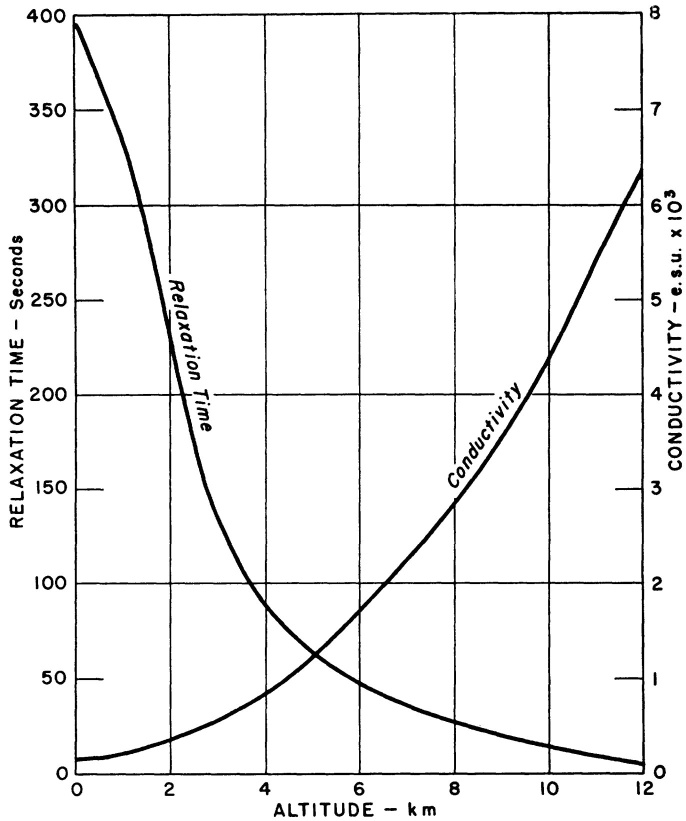

Fig. 8—Estimated electrical conductivity and relaxation time as a function of the altitude.

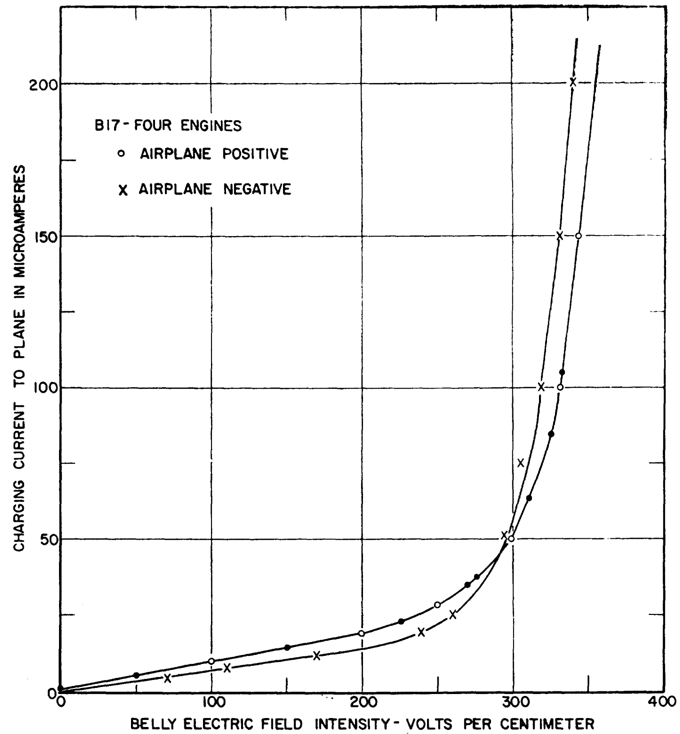

Fig. 9—Unipolar charging currents required to maintain the measured belly electric fields on B17 flying laboratory. Note that more current is required to maintain an assigned positive charge on the airplane than a negative one of the same magnitude. Note that beyond the ohmic region the discharge regime is reversed.

with respect to the altitude Z, it is found by employing a one dimensional Poisson's equation, that

$$\frac{dE}{dZ} = -\frac{E}{\lambda}\frac{d\lambda}{dZ} = 4\pi\rho. \tag{17}$$

Thus the accumulated free space charge ρ normally increases with the electric field and decreases as the conductivity becomes large. Substitution of numerical values will show that near the earth's surface space charge effects are likely to be large but at great altitudes they are not so important.

The accumulation of a space charge just outside a highly charged body and its influence on the discharge rate was particularly evident in our experimental work with the laboratory airplane of the Precipitation Static Project. An artificial charging device was invented that could place any selected *unipolar* charge on the airplane *in flight* and the current to maintain the charge could be determined as a function of the electric field [11]. We observed very early in our experimental program that the airplane charging characteristics depended on the sign of its free charge. This phenomena is well illustrated by Fig. 9, which shows that the charging current to the airplane is greatest when the airplane is positive and least when it is negative. One may notice further from Fig. 9 that as soon as the belly electric field on the airplane exceeds 300 volt/cm which corresponds to the onset of corona at the wing tips, the discharge regime is completely reversed. These observed data show very clearly that the conductivity near any surface enclosing a free charge depends on its sign. At the level of highly electrified clouds the conductivity due to the negative ions normally exceeds that due to the positive ions and therefore free positive charge commonly disappears more rapidly than free negative charge. Although such sign selective discharge effects are quite evident in charged raindrops and electrified clouds, it is still improper to conclude from this analysis and Fig. 9 that the relative discharge rates always depend *only* on the conductivities. Frequently, the discharge circuits extend both to the ground and to the ionosphere and therefore the whole electrical discharge path outside the cloud must then be considered in the over-all determination of the rates.

Highly charged raindrops of both signs commonly are observed in precipitating areas. When the conductivities due to the positive and negative ions are identical, the drops will discharge at the same rate. However, when the conductivities are different as suggested by (11) and (12), the drops of opposite sign are likely to discharge at different rates. This selective discharge process has been shown to develop free space charge distributions in the atmosphere having a considerable magnitude [27]. By using the clear air conductivity values given by (11) and (12) to illustrate the magnitudes, one may calculate how far a raindrop must fall to reduce its charge to any selected fraction of its initial value. Thus, when the

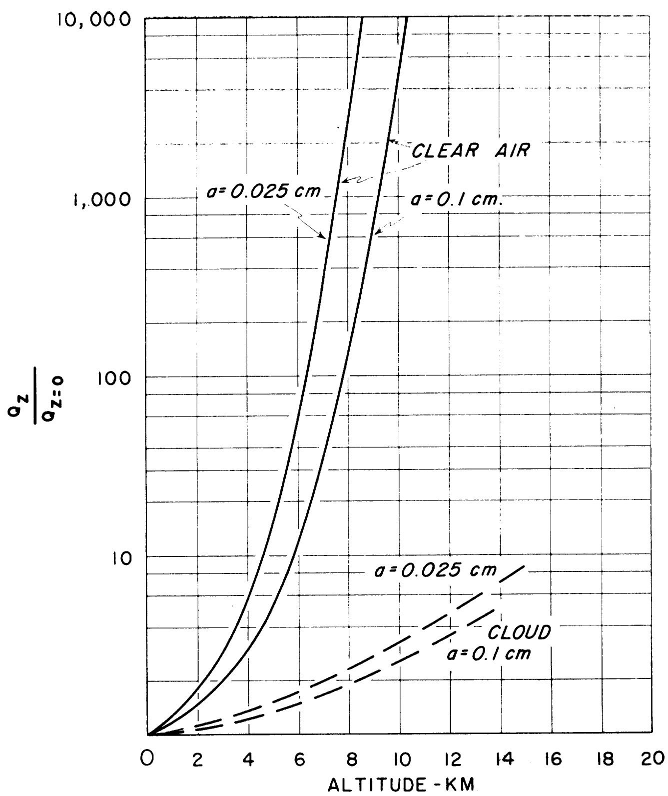

Fig. 10—Ratio of the free charge Q_z on a raindrop at level Z to its value Q_0 after falling to earth through clear air, and through stable clouds.

electrical conductivities are equal one may plot the solid curve of Fig. 10 showing the charges carried by a drop at altitude Z relative to the charge at the ground after falling through clear air. Because the conductivities inside a cloud are much less, the discharge rates are less and the estimated relative charges may be read from the dashed curve of Fig. 10. Now when the conductivities are different, one must calculate a pair of curves similar to that of Fig. 10 for positively charged and negatively charged drops [27]. The pair of curves so plotted will differ from, but still approximate, Fig. 10.

Although (11) and (12) above suggest that the positive and negative conductivities are equal at the 7-km level, we have data showing that this level sometimes is as low as 3 or 4 km. Accordingly selective charging and discharging will be evident at most rain-forming levels and there will be a marked tendency for the positive drops to discharge somewhat faster than the negative drops. Unfortunately, conditions inside a thundercloud are not quite as simple as in the clear air outside and the positive and negative conductivities inside clouds are generally unknown. However, there is accumulating evidence, for example the work of Mathias and Grenet [37], Rossmann [43], Nolan and Nolan [39], and others, all suggesting that the conductivities within a cloud or precipitating regions are much different. The differential discharge of the positive and negative drops would then be very important. The question of selective discharge in thunderstorms can only be finally settled by further measurements. Present data suggest that it plays a vital role in the establishment of free charge distributions.

Space Charge Layers and Their Effects

It has been emphasized in one of the author's articles that the discontinuity in an electrical conductivity that necessarily occurs at a cloud boundary results in the development of a space charge layer whenever the boundary is traversed by electric fields [29]. The conductivity inside a stable cloud is commonly one tenth that in the clear air just outside. Whenever free charge develops inside a cloud electrical currents flow across the boundary. Continuity requires that the equilibrium current density inside the cloud be the same as it is outside. It then follows that there is a discontinuity in the electric field at the cloud boundary just as shown by aircraft flights into thunderclouds [13, 17]. The layer of discontinuity invariably contains free space charge of a sign opposite to the charge inside the cloud. Further, since the ions produced in the atmosphere recombine or are continually deposited on the cloud droplets, an average free charge density ρ is commonly established whose magnitude is [29]

$$\rho = \frac{qe}{4\pi}\left[\frac{1}{\lambda_0} - \frac{1}{\lambda_i}\right] \tag{18}$$

where λ_0 and λ_i are the conductivities outside and inside the transition layer. Assuming that the ions in the region are produced principally by cosmic rays (*i.e.*, $q=10$ ion/cm^{3}sec) one may estimate that the space charge density is the order of 2×10^{-5} esu/cm^3. The thickness of this space charge layer is directly proportional to the electric field, although it does not explicitly appear in (18) [29]. Within a highly electrified thundercloud the thickness of the transition layer is both calculated and observed to approximate 1 or 2 km.

The space charges accumulated near cloud boundaries are at first transferred to these regions by ions but if there are cloud droplets or raindrops in this region these ions shortly are deposited on the droplets and the space charge finally resides, for the most part, on the hyper-electrified rain. This special mechanism which communicates *systematic* charges to the drops approximating $3E_0a^2$ will be discussed in another section.

The free charges inside a thundercloud always attract ions of opposite sign toward the cloud. This means that space charge established by electrical conduction will always play a secondary but clearly evident role in determining the over-all electric field configuration. For example, the character of the branching from lightning strokes shows rather clearly that free charge opposite to that inside the cloud is commonly present below most thunderclouds. This accumulated free charge is always less than the charge on the main cloud but if the principal cloud charges are suddenly annihilated by lightning, the space charge may still persist. In this event the

Fig. 11—Branching feeder strokes showing partial discharge from low clouds having same sign of charge as that induced on the earth. (Photo courtesy of Albert Ford.)

sign of the resultant charge in the overhead regions is reversed. Reference to the records of Fig. 1 will clearly show this residual charge. The residual charge manifests its presence by an *apparent over-neutralization* of the charge overhead whenever lightning discharges the main cloud. This space charge accumulated by conduction is discharged by the lightning as evidenced by the brush-like feeders to the main stroke as shown in Fig. 11, but it seems clear from the records that the discharge is commonly *incomplete*.

The Layer of Maximum Resistance at Low Levels

Because of the contamination and suspended matter in the lower 3 or 4 km of the atmosphere and its relatively high gaseous density, the conductivity of these lower layers is unusually low. Space charge is then readily developed [as suggested by (17)] and is frequently large enough to modify the electric fields and currents flowing across the layer. By the use of observed conductivity data one may show that the total resistance offered to the flow of current from the earth to the high atmosphere is located principally in these lower layers. Now if high voltages are developed between the ionosphere and the earth the ensuing currents will be independent of altitude and a large fraction of the potential difference is necessarily found across the lowest layers. The potential differences established between the top and bottom of a thundercloud are frequently in excess of 10^8 volts. This potential is applied to a closed circuit extending from the top of a cloud to the ionosphere where the charge is distributed more or less uniformly over the earth and the current flows back to the earth in the fair weather regions of the world. The rest of the circuit to the lower parts of the original thundercloud is completed through the conducting earth and through the high resistance layer between the earth and the cloud. Thus, much of the generated cloud potential difference is frequently applied across the low lying layers of high resistance. In this event lightning strokes to the ground may occur and thus, instantaneously transfer charge to the ground. Stated another way, one may notice that the ohmic resistance of these special lower layers is oftentimes so large that nature finds other auxiliary ways to transfer the rapidly accumulating free charge in the clouds to the ground. This process is suggested by Fig. 18.

It is important to notice that the mountainous areas of the earth frequently extend well above the high resistance lower layers and thus effectively provide a low resistance bypass to the high conductivity regions in the atmosphere. Electrification effects and charge transfer in mountainous areas, accordingly, play a larger role proportionately than do the oceanic areas. Eq. (17) suggests and observation shows that space charge phenomena on the tops of mountains play a somewhat lesser role than in low level layers and the distribution of charges is somewhat easier of interpretation. The study of thunderstorm phenomena in mountainous areas is, therefore, unusually important.

Electrification of Cloud Droplets

Since most raindrops are formed by the association of small melted snow crystals or cloud droplets it is important to discover the basic processes responsible for their electrification. During the last few years our laboratory has made tremendous strides in understanding these processes. These electrification mechanisms are of the greatest importance. The diffusion of ions onto the cloud droplets represents a universal process [22, 23, 26]. On the other hand, hyperelectrification and simple induction processes are of controlling importance whenever electric fields are present. Because induction and hyperelectrification [29] both depend on the presence of appreciable electric fields, they play a minor role in describing the initial phases of thundercloud electricity but may become all important after the electric field is once fully established by other electrifying mechanisms.

Laboratory clouds produced in the Weather Bureau's giant expansion chamber have provided much valuable information as to the nature of cloud electrification. The experiments show that when the cloud droplets are first formed by condensation they are all essentially neutral [46]. However, as the cloud ages, atmospheric ions diffuse onto the droplets and after an hour or so it is found that the average droplet carries about 10 elementary ions, half of the droplets being positively charged and the others negatively charged [46]. In order to establish the nature of the electrifying process studies were made of a number of different aerosols dispersed in the air by different methods [28, 46]. For example, cloud droplets formed by sudden expansion from moist air are initially neutral. A sulphur aerosol formed by the condensation of sulphur vapor is similarly neutral. On the other hand, a finely divided cloud of silica particles blown into the air by an air blast are found to be highly electrified both positively and negatively [46]. Water droplets atomized by an air blast are also highly electrified. In spite of the complexities suggested by the above differences in initial behavior of newly formed dust and water clouds, we have discovered that for droplets of the same size the electric charge magnitude and distribution are

TABLE IV*

Number of Collisions	Number of Unit Charges q																				
	−10	−9	−8	−7	−6	−5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9	+10
0											1000										
1										500		500									
2									250		500		250								
3								125		375		375		125							
4							62.5		250		375		250		62.5						
5						31.2		156		312		312		156		31.2					
6					15.6		93.7		234		312		234		93.7		15.6				
7				7.8		54.6		164		273		273		164		54.6		7.8			
8			3.9		31.2		109.0		218		273		218		109.0		31.2		3.9		
9		1.9		17.5		70.3		164		246		246		164		70.3		17.5		1.9	
10	0.9		9.7		43.9		117.0		205		246		205		117.0		43.9		9.7		0.9

* Beginning with 1000 neutral drops, the table gives the probable number of drops carrying the assigned numbers of unit charges indicated in the top horizontal line, after suffering the number of unit charge transferring collisions shown in the left-hand column. Note that the distribution after a number of collisions is nearly Gaussian.

finally exactly the same no matter how the cloud is first produced *provided the aerosol is aged by exposure to copious ionization* [46]. This ionization may be produced by cosmic rays, X rays, or any other suitable ionizer. Since the final equilibrium charge distribution of an aerosol is the same irrespective of the original neutral or highly electrified condition and since the equilibrium depends on the presence of ionization, it is clear that the atmospheric ions are responsible for their charges. The time required to establish the charge equilibrium on cloud droplets is comparable to the value given in (15). But it may be noticed that the potential of the typical cloud particle does not finally approach zero as suggested by (14) but rather a value something less than kT/e. Thus each cloud droplet in the semiconducting atmosphere acts as though it were a tiny electrical concentration cell [10].

The electrification of cloud droplets by diffusion plays an important role in the mechanics of precipitation. When the cloud droplets are electrified like those in Figs. 14 and 16 the establishment of electric fields throughout the cloud may profoundly modify the collision processes and the resulting stability. For example, we have shown that when the electric field exceeds about 2 statvolt/cm the electrical forces may sometimes be as effective as gravity in promoting precipitation [24]. Thus, in the presence of high fields the rate of precipitation may be greatly increased. Indeed, there is evidence to suggest that this process is responsible for the so-called "rain gush" sometimes observed in thunderstorms.

The Diffusion Charging of Droplets in an Ionized Atmosphere

It has been found possible to show from the ordinary classical diffusion equations that the bombardment of droplets by ions describing free paths as a result of their thermal kinetic energy, act to establish a Gaussian-like distribution of positive and negative drops just like that observed. The fundamental mechanisms may be understood by reference to Table IV. Suppose that cloud droplets are suspended in the air where there are n_+ positive ions and n_- negative ions per unit volume, and suppose further that their mobilities are u_+ and u_- respectively. Because of the thermal motions of the ions, the ratio of the probability of a positive ion striking a droplet as compared to the probability of a strike by a negative ion is n_+u_+/n_-u_-. For illustration, suppose that the probability of a droplet acquiring a positive ion is exactly the same as the probability of it capturing a negative ion. Now, if there are a thousand droplets initially, after one ionic collision, 500 droplets will acquire a positive ion and 500 will pick up a negative one. When these electrified droplets capture a second ion, half of the droplets in each new group will acquire a positive ionic charge and the other half a negative charge. Thus, after two collisions 250 droplets will have two negative charges, 500 will be neutral, and 250 will have two positive charges. By carrying out this procedure for each succeeding collision one may show as in Table IV that a distribution is established in which equal numbers of positive and negative cloud droplets are present and the Gaussian-like distribution will be symmetrical about the axis of zero charge. It is especially important to notice from Table IV that the mean charge on the cloud droplets is many times the charge on the parent ions.

It frequently happens that the number of positive and negative ions or their mobilities are different, and this modifies the relative probability of collision. One may easily construct another table in which the probabilities of collision for the positive and negative ions are different [32]. The reader may verify that a distribution is established here also, but the maximum is displaced systematically towards the sign of the droplet charge having the highest probability of collisions.

It should be emphasized here that Table IV describes only the initial phases of the electrification and one may show that as the number of collisions increases to large values, sufficient charge is transferred to the mean drop to reduce the probability of collision with ions of the same sign and increase the probability of collision with ions of the opposite sign. Under such conditions an equilibrium charge is established. This conclusion is

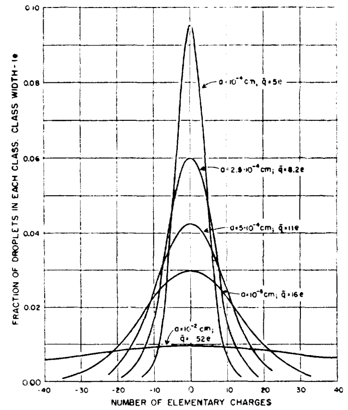

Fig. 12—Distribution of the fractional number of cloud droplets carrying assigned numbers of elementary charges and having different radii. The mean charge, $\bar{q}$, irrespective of sign, is indicated on each curve. Distribution calculated from (19) with $\lambda_+/\lambda_- = 1$.

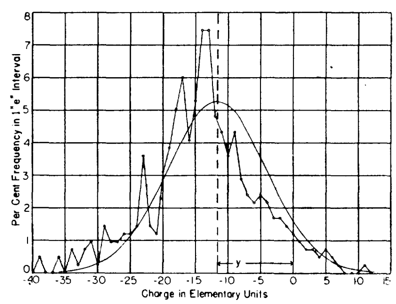

Fig. 13—Measured fractional number of water droplets carrying assigned numbers of elementary charges. Average radius 3.3μ. Measured conductivity ratio $\lambda_+/\lambda_- = 0.82$ so that average free charge is -11.7 elementary units. Smooth curve is calculated from (19).

based on a careful analysis of the dynamical equilibrium established by diffusion as recently worked out by the author [22, 23]. It is sufficient to mention here that by applying well-established laws describing the motion of particles subject to electric fields and diffusion, one may work out the rate at which ions are transferred and accumulated on a spherical droplet. From these relations it is possible to determine the resulting distribution through a theorem on detailed balancing at equilibrium [23]. In an assemblage of a large number of droplets of common radius a immersed in an environment wherein the ratio of the positive and negative light ion conductivities is λ_+/λ_- we have shown that

$$\frac{F_x}{F_t} = \frac{e}{(2\pi akT)^{1/2}} \exp\left\{\frac{-\left(x - \frac{akT}{e^2}\ln\frac{\lambda_+}{\lambda_-}\right)^2}{\frac{2akT}{e^2}}\right\} \tag{19}$$

where F_x is the number of droplets carrying x elementary charges of magnitude e, F_t is the total number of droplets, k is the Boltzmann constant, T is the absolute temperature, and e is the elementary electronic charge. *This is the fundamental electrification equation for aerosols* [23], and includes both the statistical and systematic charging. The distribution calculated from (19) for a number of different droplet sizes is shown in Fig. 12 when $\lambda_+/\lambda_- = 1$. By integration of (19) one may determine an average number of elementary charges, irrespective of sign, carried by the aerosol particles. From this it is found that [23]:

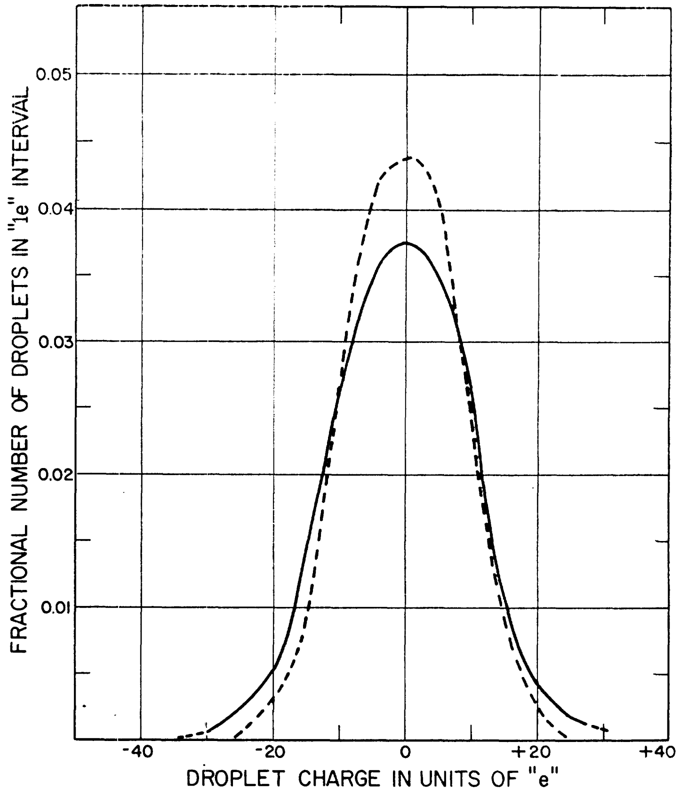

Fig. 14—Observed droplet charge distribution in natural cloud. Radius $=4\mu$. Electric field small. Dotted curve calculated from (19).

$$\frac{\bar{q}^2}{2a} = \frac{\pi}{4} kT \tag{20}$$

where $\bar{q}$ is a previously defined mean charge, averaged without respect to sign [23]. Now since a is essentially the electrical capacity of the droplet, the terms on the left-hand side represent the stored electrical energy, while kT is the probable thermal kinetic energy. Thus an *equipartition* is established between the *electrical* and *thermal energies* of the droplets when equilibrium is finally reached.

The fundamental electrification expression of (19) has been well tested in the laboratory. It may be noticed particularly that when the ratio of the probabilities for capture of positive and negative ions or λ_+/λ_- is different from unity, then the curves in Fig. 12 are systematically displaced [28]. An experimental measurement of the distribution under carefully controlled conditions with $\lambda_+ \neq \lambda_-$ is shown in Fig. 13. The measurements are fully consistent with the basic equation.

For the purpose of comparison with the analysis just indicated, one shows in Fig. 14 the distribution observed in a *natural cloud* on the top of Clingman's Peak, N. C. This cloud was relatively stable and the electric field at the point of measurement was negligible. Thus, in accordance with (19), the distribution would be expected to correspond to $\lambda_+ = \lambda_-$ and be symmetrical about the zero charge axis.

Systematic Electrification by Ionic Diffusion $\lambda_+ \neq \lambda_-$

Droplets maintained in an environment wherein the electrical conductivities for the positive and negative ions are different all develop a systematic electrification of preferred sign. This phenomenon is illustrated in Fig. 13. When the cloud particles are sufficiently small the distribution coincides with (19) above, but whenever there is appreciable relative motion between the droplet and its ionized environment this motion modifies the ionic density gradient around the droplet and increases the systematic charge. It may be shown that under these circumstances the falling droplet acquires a mean systematic charge [22] given by

$$Q = \left[1 + F \frac{aVe}{2\pi kTu_\pm}\right]^{1/2} \frac{akT}{e} \ln \frac{n_+u_+}{n_-u_-} \qquad (21)$$

where F is a numerical constant of the order of unity, V is the velocity of fall of the droplet, $u_\pm$ is the mobility of the mean ion in the transition layer next to the droplet, and $n_+u_+/n_-u_- = \lambda_+/\lambda_-$. The enhanced electrification due to the motion of the droplet is by no means negligible, because large raindrops falling in a field free region can easily accumulate 20 times the charge that would be developed were the drop maintained at rest. The essential correctness of (21) has been verified by laboratory measurements employing a small wind tunnel supplied with ionized air [42].

It is clear from (19) and (21) that no *systematic* charge is transferred to the droplets whenever the positive and negative light ion conductivities are equal. According to an earlier investigation this conductivity ratio depends notably upon the number of particles suspended in the air and their radius [31]. The relationship is specified in Fig. 15. Thus, in a typical stable cloud where $N_0{}^2a^2/q$ is large the droplet charges are distributed at random and no systematic electrification is produced. However, in those special regions where there are relatively few droplets or snow flakes per unit volume the conductivity ratio may be much different from unity and considerable systematic electrification produced. (See Fig. 13.) Recent work has shown that rain is initiated in typical warm clouds when parcels of nearly nuclei free air are lifted near the tops of clouds [33]. The droplets then formed by direct condensation are abnormally large and examination shows that the conditions for their production are just those required systematically to electrify them. In the presence of sufficient cooling these droplets may grow to produce raindrops carrying charges of moderate size. Such systematic droplet electrification plays a part in the *initiation*

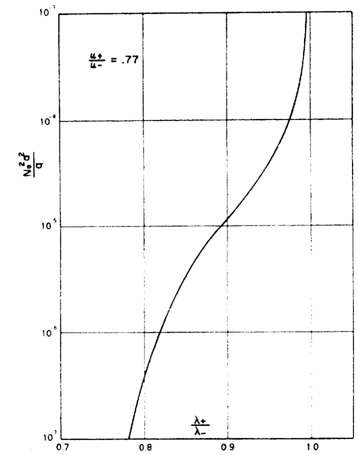

Fig. 15—Calculated relation between $N_0{}^2a^2/q$ and the ratio of the light ion conductivities λ_+/λ_-.

of electric fields. Since the process can electrify either snow flakes or droplets it is clear that even warm clouds may develop lightning [6, 24, 25].

Hyperelectrification of Cloud Droplets in an Electric Field

Many suggestions have been made as to ways that cloud and raindrops might acquire their charge [36, 47]. Space does not permit a general discussion of this interesting problem and one considers here only those electrification processes that are thought to be so energetic that they probably control the basic phenomena. As emphasized above, ionic diffusion is a universal phenomenon and it is, therefore, particularly important whenever electric fields are not present. However, it is well known that electric fields are commonly generated by precipitation and in their presence very energetic droplet electrification is produced by other processes.

Consider a slightly conducting sphere immersed in an electric field. It becomes polarized and free charges of opposite sign are induced on the opposite polar surfaces. When this polarized sphere is maintained in a conducting atmosphere, the positive ions migrate to the negatively charged areas and the negative ions migrate toward the positive. A careful analysis of this process shows that if the conductivities of the positive and negative ions are equal the sphere accumulates no net charge. On the other hand if the conductivities are notably different the sphere acquires a free charge comparable to the charge induced near its poles or $\pm 3E_0a^2$ [29]. This process might not be particularly important were it not for the fact that atmospheric electric fields invariably sweep ions of a single sign into extensive space charge or transition layers that mark gross discontinuities in the electrical conductivity. In such transition layers the conductivity ratios may be very large and all the droplets maintained in this region become highly electrified and all have the *same sign*. On the other hand, a cloud composed of several parts, each separated by clear air, will produce drops of opposite signs on the adjacent faces of the juxtaposed sections. A mixture of charges may then be anticipated. The magnitude and reality of this process which we have called *hyperelectrification* has been established in the laboratory [29]. The magnitude of the charge transferred to such polarized spheres is [29]

$$Q = 3E_0a^2\left[\frac{(\lambda_+/\lambda_-)^{1/2} - 1}{(\lambda_+/\lambda_-)^{1/2} + 1}\right]. \tag{22}$$

The specific charge is therefore

$$\frac{Q}{M} = \frac{9E_0}{4\pi ad}\left[\frac{(\lambda_+/\lambda_-)^{1/2} - 1}{(\lambda_+/\lambda_-)^{1/2} + 1}\right] \tag{23}$$

where d is the bulk density of the drops. As an example of hyperelectrification consider Fig. 16 representing the charge distribution on natural cloud droplets observed on top of Clingman's Peak when the cloud droplets were exposed to measured electric fields. It may be noticed that all of the droplets are highly electrified and carry only a negative charge. The observed distribution may be related to variations in droplet size but their mean value is indicated in the caption of the figure. The new data of Figs. 14 and 16 were kindly made available through Dr. Gilbert D. Kinzer.

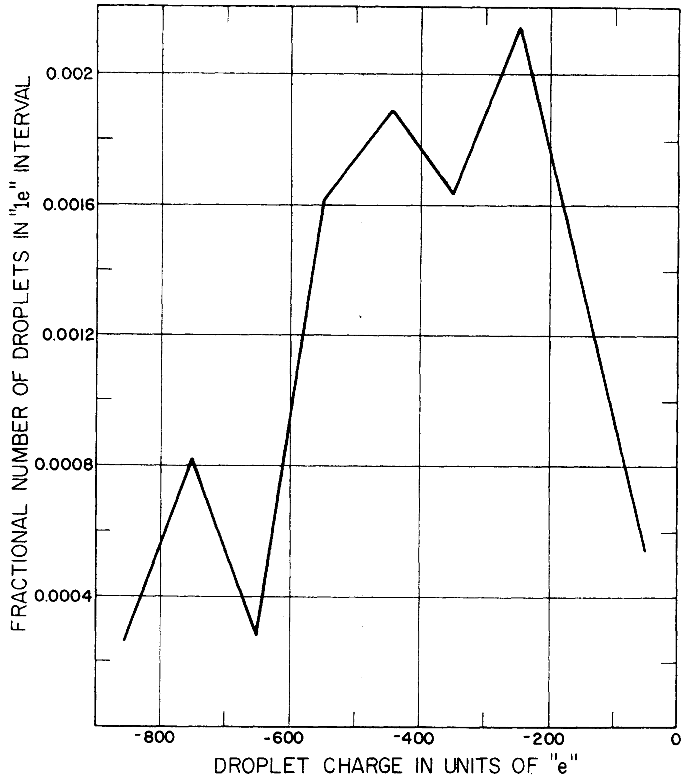

Fig. 16—Droplet charge distribution observed in natural cloud. Radius 8μ. Electric field $\neq 0$. An example of hyperelectrification.

Electrification by Induction of Colliding but Nonassociating Snow Flakes and Raindrops $E \neq 0$

Some of the following sections emphasize the enhanced electrification that may be transferred to falling rain as a result of the association of large numbers of electrified cloud droplets. There is, however, a special case of considerable importance wherein electrical effects are produced *because the particles do not associate* or because they breakup in an electric field. Ice crystals and individual snow flakes are commonly formed at high levels where the temperature is below freezing and these grow to appreciable size by direct condensation of the water vapor. These snow flakes fall at different velocities and frequently collide but thereafter may immediately separate because no surface tension forces promote association as in water droplets. Whenever an electric field is present the snow flakes are polarized and on contact may exchange charge. It is clear that if the colliding particle are favorably oriented with respect to the electric field their separation may produce a highly charged positive and negative pair. In a somewhat similar way raindrops that collide and immediately separate instead of associating will have opposite charges on the separated drops. It is well known that raindrops having a radius greater than about 0.25 cm, commonly break up. Large charges of opposite sign will then be produced by induction on the resulting smaller drops.

Recently Müller-Hillebrand [38] has revived the well-known Elster and Geitel [5] mechanism by showing that ice crystals in collision with graupel possess sufficient conductivity to permit an exchange of charge and thus become systematically electrified. The Müller-Hillebrand processes may very well contribute to the electrification but the simple induction processes are much more energetic.

Consider a large number of snow flakes falling in the cold high atmosphere. These flakes are of different sizes and have different aerodynamic properties so that there is relative motion between all the particles and collisions are moderately frequent. Suppose that any two flakes or any two nonassociating raindrops may be thought of as two similar polarized slightly conducting spheres. Now if they collide in such a way that the line joining their centers is in the direction of the electric field, then one may show that the free charge induced on each sphere has a magnitude given by

$$Q = \frac{\pi^2}{3} E_0a^2 \tag{24}$$

where E_0 is the impressed electric field and a is the radius of the spheres. Upon separation one sphere will carry a positive charge and the other a negative charge of the same magnitude. When the orientation is random, the average charge will be some appreciable fraction of (24). Because the separating components are of opposite sign they will attract each other and in some cases the initial relative kinetic energy between the particles will be insufficient to separate them. Accordingly, the induction process will be important only when the relative kinetic energy is greater than $Q^2/2a$. It can be shown that such a requirement is met in most cases and perhaps most snow or ice crystal collisions and nonassociating raindrop collisions result in oppositely charged *pairs* of magnitude comparable to (24). Such simple induction processes have a marked advantage over other mechanisms because the charging is instantaneous and does not depend either on the generation or on the capture of ions. The mechanism is believed to be of considerable importance. From (24) it follows that the charge per unit mass or the specific charge irrespective of the sign is $Q/M = \pi E_0/4ad$.

Electrification by induction is highly efficient and energetic so that when this process is common, a mixture of snow flakes or raindrops carrying *nearly equal positive and negative charges will be found in the atmosphere.* Because the charges transferred to each particle are proportional to the electric field, flakes falling near the freezing level where the field is normally large are likely to be highly electrified and if they further associate to form rain *after they melt*, extraordinary high drop charges may be anticipated. The Graupel forming stage, therefore, is likely to transfer excessively large free charges to the drops. Indeed, calculations suggest that corona will be discharged from a small percentage of them [32].

Attention is drawn to the fact that the free water necessary to produce a snow flake is only about 1/50 that for a spherical water drop of the same size [34]. Since the charge induced on each separating flake is proportional to the square of its linear dimensions, it is clear that snow crystals electrified by induction in an appreciable electric field may produce relatively *large free charges per unit mass.* In the next section we will consider the electrical effects produced when such highly electrified snow flakes melt to form droplets and these further associate to produce enhanced electrification.

Enhanced Electrification by the Association of Electrified Droplets to Form Rain

Enhanced electrification is always produced whenever electrified cloud or rain droplets collide and associate to form rain [24, 25, 32]. Analysis shows that if the cloud droplets are all of one sign the association simply concentrates these free charges on the raindrops and the free charge is conserved. On the other hand, if the parent cloud droplets are composed of a mixture of positive and negative charges the association processes neutralize some of the available free charge. However, the statistics of the processes are such as to establish a mixture that effectively preserves an appreciable fraction. (See Table IV.) This charge is distributed more or less equally among a large number of drops each of which may sometimes carry thousands of the original cloud droplet charges [24, 25, 32].

According to the results of earlier sections a typical cloud consists of large numbers of droplets in which about half of the droplets carry a positive charge that is typically 11 elementary units while the other half typically carries 11 negative units. Normally 4 per cent or less of the droplets are uncharged. Suppose that a small raindrop falls down through such a cloud and grows by association thus consolidating the charges carried by the cloud droplets. The falling raindrop is accordingly bombarded in a purely random manner by the cloud droplets which it successively intercepts. If there are equal numbers of positively and negatively charged droplets the probability of the drop colliding with a positive droplet is the same as the probability of it colliding with a negative droplet. The statistical distribution of charge may, therefore, be worked out in a manner precisely like that used to determine the charge on the cloud droplet when it was bombarded by ions. The exact process is well illustrated by Table IV. The fundamental difference between the electrification of the cloud droplet and the raindrop is that the cloud droplet encounters ions by virtue of their thermal agitation, whereas the raindrop is bombarded as a result of the relative gravitational motions of the large raindrop and the small electrified droplets.

Two raindrop electrifying regimes by droplet association are evident. The initial or nonequilibrium regime describes the early stages of electrification and is descriptive as long as the probability of collision of a droplet with a charged drop in constant. This regime is gradually converted into the equilibrium regime which is established whenever accumulated raindrop charges become large enough to control the probability of collision.

The Initial or Nonequilibrium Regime

Whenever the number of collisions between the raindrop and the cloud droplets is limited and the probability of collision is constant, the *average* charges *for the distributions* illustrated by Table IV may be estimated by use of the binomial point equation of statistical theory. It has been shown [32] that the mean nonequilibrium charge accumulated on raindrops $\hat{Q}$, *averaged without regard to sign*, is nearly

$$\hat{Q} = \left[\frac{2K}{\pi}\right]^{1/2} \bar{q} \tag{25}$$

where K is the number of collisions that establish the charge on the raindrop and $\bar{q}$ is the mean charge on the parent droplets, irrespective of their sign. The value of $\bar{q}$ may be given by (20) or by (24). Since K may be large it is clear that very large drop charges may sometimes accumulate.

In the special case where there are more cloud droplets carrying one kind of charge than the other, and their numbers per unit volume are C_+ and C_-, it is found [32] that the mean *systematic* charge $\overline{Q}$ accumulated on the raindrops *averaged with respect to sign* is

$$\overline{Q} = \left\{\frac{\dfrac{C_+}{C_-} - 1}{\dfrac{C_+}{C_-} + 1}\right\} K\bar{q} = \frac{K\bar{q}}{2} \ln\left(\frac{C_+}{C_-}\right) \tag{26}$$

where the logarithmic form is applicable only when C_+ and C_- are not too different. The above nonequilibrium expressions for the raindrop charges are of value only when the number of collisions can be specified. Although other assumptions are possible, it is illuminating to suppose that the number of collisions is determined only by the ratio of the mass of the final drop to the mass of the average colliding cloud particle. Under this condition the random specific charge or the charge per unit mass accumulated on the falling rain, when averaged without regard to sign [32], is given by

$$\frac{\hat{Q}}{m_2} = \left[\frac{2fm_1}{\pi m_2}\right]^{1/2} \frac{\bar{q}}{m_1} \tag{27}$$

where $\bar{q}/m_1$ is the random specific charge carried on the parent droplets, m_1 and m_2 are the masses of the cloud and raindrops, respectively, and f is an unknown factor that measures the evaporation, breakup of the drop, etc., and approaches unity when these factors are negligible. In a similar way the systematic specific charge transferred to the falling rain is [32]:

$$\frac{\overline{Q}}{m_2} = \left[\frac{C_+ - C_-}{C_+ - C_-}\right] f \, \frac{\bar{q}}{m_1}\,. \tag{28}$$

This expression shows that the systematic *specific free charge is conserved* during drop growth.

The Equilibrium Electrification of Raindrops

When there are sufficiently large numbers of collisions with the cloud droplets or when the cloud droplets are highly electrified an equilibrium distribution much like that given in (19) may be established. The fractional number of raindrops carrying integral multiples of the mean cloud droplet charge $\bar{q}$ is essentially a Gaussian distribution. This distribution is normally symmetrical about the zero charge axis whenever equal numbers of positive and negative cloud droplets are encountered, but may be radically skewed towards positive or negative charges when the population densities C_+ and C_- of the positive and negative parent cloud droplets are appreciably different. When equilibrium is established one may show [24, 25] from the mathematical analysis that

$$D_{\Omega\bar{q}} = \frac{D_t \bar{q}}{\left[\dfrac{\pi(r_1 + r_2)U_R^2}{2\left(\dfrac{1}{m_1} + \dfrac{1}{m_2}\right)}\right]^{1/2}} \cdot \exp\left\{\frac{-\left[\Omega\bar{q} - \dfrac{(r_1 + r_2)U_R^2 \ln (C_+/C_-)}{4\bar{q}(\{1/m_1\} + \{1/m_2\})}\right]^2}{\dfrac{(r_1 + r_2)U_R^2}{2\left(\dfrac{1}{m_1} + \dfrac{1}{m_2}\right)}}\right\}. \tag{29}$$

In this expression D_t is the total number of raindrops per unit volume, $D_{\Omega q}$ is the number per unit volume carrying a charge $\Omega\bar{q}$, $\bar{q}$ is the mean parent droplet charge, irrespective of sign, Ω is an integral number, m_1, m_2 and r_1 and r_2 are the masses and radii of the cloud and raindrop respectively and U_r is the relative velocity of the two types of drops. The ratio of the number of parent positive cloud droplets to those carrying negative charges is C_+/C_-. It may be noticed that this expression is similar in form to (19) and analogous to it in many ways. Thus one may calculate the mean charge on both the positive and negative *fractions* of the falling rain and show that this charge is given [25] by

$$Q_+ = \left[\frac{\pi(r_1 + r_2)U_R^2}{8\left(\dfrac{1}{m_1} + \dfrac{1}{m_2}\right)}\right]^{1/2} = \overline{Q}_-. \tag{30}$$

Like (19) this may also be rewritten to show that an approximate *equipartition* is established wherein the electrical potential energy carried by the average falling raindrop is equal to the energy of bombardment by the smaller cloud particles.

One may emphasize that the equilibrium charge described by the above equations is not always established in ordinary rain because of the limited distance of fall or limited numbers of collisions. This is particularly true when the cloud droplets are weakly electrified as by ionic diffusion. As a rough guide, the equilibrium distribution of (29) and (30) may be used whenever a mixture of highly electrified droplets is produced as by induction. The nonequilibrium expressions of (27) and (28) are used when the droplets are weakly electrified as by the diffusion processes. No general rule is applicable and a special examination must be made in doubtful cases [32].

Maximum Accumulated Drop Charges

In an earlier analysis of the electrical charges measured on the ground and on aircraft flying through active thunderstorms, it was pointed out that the raindrop electrification processes must be extremely energetic because large numbers of drops of both signs were observed, each of which carried charges so large that the electric field at their surface was an appreciable fraction of the dielectric strength of air [14]. Reference to Table II will show that direct measurement of the charge on thunderstorm rain suggests charges approximating ± 0.1 esu/drop. Now, if the drop corresponds to "medium rain," its radius will approximate 5×10^{-2} cm. The electric field at the drop's surface, therefore, is about 40 statvolt/cm or 12,000 volt/cm. When one reflects that such drops approach small conducting cloud particles that may locally concentrate the electric field, and notes further that the drop is frequently deformed as a result of aerodynamic forces, it is clear that adequate fields may exist at the drop surface to produce a corona discharge. Actually, the conditions necessary to induce corona are more complex than the above statement implies. It has been long known that a certain minimum voltage is necessary as well as a large electric field. In small droplets the voltage is so low that electric fields exceeding the normal dielectric strength of air will not cause discharge but drops as large as the example used above may very well exceed the critical value and transfer by corona discharge any excess charge to the surrounding air [14]. It seems clear from the data in Table II and from other measurements made in active thunderstorms near the rain-forming levels, that many of the larger raindrops are "fully charged" by the acting electrification processes.

Free Charge Distributions and Their Separation

Whenever equal amounts of positive and negative electricity are found within a given volume, it is neutral and no systematic electric fields are produced. In a thundercloud consisting of a mixture of highly charged raindrops, electrified cloud droplets, and ions, it is *not likely* that such a condition of exact neutrality will long persist. Consider a great neutral sheet of rain and cloud droplets. The rain falls faster than the cloud particles and an initial neutrality is shortly replaced by a free charge distribution. For example, negative charges largely carried by rain generally appear near the bottom of high level clouds while positive charges are likely to remain above. By considering a vertical prism of unit cross section extending from the ground through the thundercloud one may calculate the electric field E and the total charge per unit area within the prism by integrating Poisson's equation

$$E = 4\pi \int \rho dz = 4\pi\sigma + E' \tag{31}$$

where ρ is the free charge per unit volume, σ is the integrated free charge per unit area, and E' is the constant of integration determined by the surface charge. In this way one may formally determine the field in terms of the separated free charges on the precipitation and on the ground [10].

In addition to the free charges carried inside the cloud there are invariably charges induced on the conducting ionosphere and on the earth below. These induced charges play an important role in transferring electricity to the earth. The induced and free charge per unit areas within the prism are usually so adjusted that the total is approximately zero. In typical cases the electric field within the active region of the thundercloud is downward. But near the ground and above the cloud, the field is positive and outward. Sometimes the whole configuration is reversed. Usually the separation of free charge establishes fields that not only induce charges on the high atmosphere and the ground but simultaneously transport ions towards charge centers and thus establish space charge sheets that act to limit the intensity of the electric field as measured at the earth's surface. This effect is prominent in the observed reversal of the field after a lightning stroke (Fig. 1).

According to the direct measurements reported in Table II above, the rain inside an active thunderstorm may consist of nearly equal numbers of positively and negatively charged drops or in some cases drops carrying a single sign are observed. When a matrix consisting of equal numbers of equally charged positive and negative drops are present in the air and both types fall at the same velocities, it is clear that no free charge separation or electric fields are produced. On the other hand, if the larger raindrops carry predominantly charge of one sign, neutrality of any given volume of space cannot be maintained and the big drops carrying their selected charge will fall, leaving their neutralizing charges of opposite sign to fall at a slower rate. A progressive separation of free charge by this means steadily increases the electric field. The accumulation of separated free charge cannot continue for long, because according to (31) electric fields of progressively greater intensity are immediately established and these fields interacting with the charge on the droplets produce electrical forces that act to oppose and limit the separation. In some cases these forces are adequate to support many of the raindrops against the forces of gravity [10].

One may emphasize that in most cases the free positive charges are never completely separated from the free negative charges. For example, in a mild cold front exhibiting charges like those summarized in Table III, it was found that the free charges corresponding to those measured on the large drops and distributed through a spherical volume a kilometer or so in radius would establish electric fields at the surface of the sphere many times as large as that actually measured. This shows that the charge separation is incomplete and that, in nature, there is always a mixture of positive and negative charges. However, one sign may be somewhat in excess [17]. This same conclusion is reached by calculatint the approximate free space charge density from the observed space gradients of the electric field values, and comparing this value with the free charges directly measured on the precipitation. The charge on the precipitation alone is again several times the net space charge showing that neutralizing charges, not measured by the raindrop analyzing equipment are present and mixed with the highly charged rain. Thus it is always necessary to distinguish carefully between the drop space charge density and the net space charge density [12].

According to the foregoing observations made inside actual storms one is brought to the view that a typical thunderstorm cloud is composed of large amounts of free charge of both signs carried partly by large raindrops, partly by small cloud droplets, and partly by ions. In this matrix, the heavily charged raindrops always fall towards the earth and when they carry charge predominantly of a single sign, then a convective or transport current is produced carrying charge towards the ground and separating free charge. The magnitude of this convective current density [18] is given by

$$i = \Sigma N_+ Q_+ V_+ + \Sigma N_- Q_- V_- = \rho \overline{V} \tag{32}$$

where N_+ and N_- are the numbers of large raindrops per unit volume carrying positive and negative charges respectively. Q is the charge on each, $V_\pm$ is the velocity of fall of the drops; ρ is the net free space charge density; and V is its effective falling velocity. The velocities of fall for large drops is primarily determined by the aerodynamic forces and by gravity. But the smaller drops develop lower velocities that may be somewhat influenced by the electric fields.

It is clear from the foregoing paragraphs that gross electrification is not likely to be established within a cloud unless some mechanism selectively transfers free charge to the larger raindrops. One has, therefore, to examine the possible processes which can transfer free charge to rain. That such selective charging frequently occurs is fully demonstrated [12, 17, 19] by detailed plots of the summarized data. For example, in both the thunderstorm in the mild cold front mentioned above, *regions were observed wherein the large precipitation elements all carried charges of the same sign.* Neutralizing charges doubtless were associated with these but were attached to the smaller particles that would fall at a very much slower speed. Thus, according to (32) a net convective current is established.

Hyperelectrification provides an energetic mechanism for placing charges, all of one sign on large number of raindrops. We have shown that near the boundaries of electrified clouds, ions of a selected sign are concentrated; these ions are transferred to the polarized raindrops immersed in the layer and selectively charge them to a value given by (22). Now within the boundary space charge layer the positive and negative light ion conductivities are normally much different so that the drop charges are generally of one sign.

The number of raindrops or snow flakes in unit volume is determined by the liquid or crystalline water content (LWC) of the cloud and the droplet mass, so that the convected current density i of (32) in the case where all drops carry the same sign of charge, as for example, in hyperelectrification, is

$$i = (\mathrm{LWC}) \frac{Q}{M} V \tag{33}$$

where the velocities of fall V may be determined nearly enough from available Tables of terminal velocities [16].

Earlier paragraphs have noticed that a mixture of highly charged positive and negative raindrops can be established either by induction in an electric field or by the association of large numbers of oppositely electrified cloud or rain droplets. Irrespective of the processes whereby such a mixture is produced, drops, falling down through an atmosphere wherein the positive and negative light ion conductivities are different, will selectively discharge drops of one sign more rapidly than they will discharge those of the opposite sign. This process results in the accumulation of raindrops at lower levels having a predominant free charge [27]. Whenever the initial specific charge of the mixed raindrops is sufficiently large and the differences in electrical conductivity are considerable, the convected current densities are large enough to establish measurable electrical activity [27]. The difference in conductivities between the positive and negative ions is established only for clear air as shown by (11) and (12) but there is accumulating evidence [37, 39, 43] to show that the conductivities are frequently much different inside natural clouds or in precipitating regions. Whenever the raindrops fall some kilometers in an atmosphere wherein $\lambda_+ \neq \lambda_-$ we have been able to show that the current density established by the above differential discharge processes is given roughly by [27]:

$$i = \frac{\mathrm{LWC}}{2}\left(\frac{Q}{M}\right) V \left[\exp(-1) - \exp\left(\frac{-\lambda_+}{\lambda_-}\right)\right] \tag{34}$$

where λ_+/λ_- is the ratio of the conductivities of the environment through which the drops fall.

It is convenient to recognize that the product of the liquid water content and its effective velocity of fall corresponds to the mass precipitation rate P expressed in terms of grams per square centimeter per second and therefore the convected current density may always be represented by an expression of form

$$i = (\mathrm{LWC}) \frac{Q}{M} V \phi(\lambda_+/\lambda_-) = P\left(\frac{Q}{M}\right)\phi(\lambda_+/\lambda_-) \tag{35}$$

where the function $\phi(\lambda_+/\lambda_-)$ measures the fraction of the total drop charge Q that is preserved as a free or systematic charge. This fraction depends on the particular drop electrifying mechanism and commonly approximates values from 0.05 to 1.0.

The energetic processes capable of highly electrifying rain that is exposed to electric fields have been emphasized above. There are, in addition, other electrification means that may contribute to the establishment of thunderstorm activity. For example, melting hail may place an excess positive charge of more than 1 esu on each gram that melts and falls to lower levels [4]. Similarly, the selective transport of ions to cloud droplets in regions where the positive and negative light ion conductivities are notably different can, according to (21), produce specific charges of 1.0 esu/gm under favorable conditions [26]. This latter process is of some importance in describing the initial electrification induced by low level nonthunderstorm rain.

Equilibrium Electric Fields and the Regeneration Time

Because electric fields are easily measured, it seems important to express the charge transferring processes in terms of the established field. Consider for example the downward transfer of a horizontal sheet of negatively charged raindrops and assume that the positive charge remains essentially fixed on the smaller cloud droplets above. Earlier articles [18, 20] considered the equilibrium in a vertical prism of unit cross section extending from the earth through the thundercloud. It was shown that in this prism

$$\frac{1}{4\pi}\frac{dE}{dt} + \lambda E = \Sigma NQV = \rho\overline{V} = i. \qquad (36)$$

The first term expresses the accumulation of free charge per unit area below a selected reference plane, the second term the conduction current density, and these are equal to the convective current density i. The solution of (36) is

$$E = \frac{\rho\overline{V}}{\lambda}\left[1 - \exp\left(-4\pi\lambda t\right)\right] + E_1 \exp\left(-4\pi\lambda t\right) \quad (37)$$

where E is the generated electric field at the reference plane, E_1 the field at the plane when $t=0$, λ the total electrical conductivity of the environment, ρ the net free charge density carried by the large raindrops, and $\overline{V}$ is the fall velocity of the heavy drops relative to the much smaller ones that carry the neutralizing or partially neutralizing charges. It is clear from (36) that when an equilibrium electric field is established, the charge accumulating below the reference plane approaches zero and the downward convected current density is just balanced by the upward conduction current density. Thus the equilibrium electric field approximates

$$E_e = i/\lambda = \frac{\rho\overline{V}}{\lambda}\cdot \qquad (38)$$

Now immediately after a lightning discharge, E_1 is small and therefore by (37) one has approximately

$$\left(\frac{dE}{dt}\right)_0 = 4\pi\rho\overline{V} = 4\pi i. \qquad (39)$$

Here $[dE/dt]_0$ is the *initial* rate of increase of the electric field just after the thundercloud has been neutralized by a lightning discharge. Thus, if the electric field recovers logarithmically as suggested by (37), the time τ_R it will take the convection current to raise the electric field to a value E_c is given by [20]:

$$\tau_R = \frac{E_c}{4\pi i} = \frac{E_c}{4\pi\rho V}\cdot \qquad (40)$$

It is illuminating to identify this critical field E_c with the dielectric strength of air and then τ_R may be identified with the time to regenerate an electrical state capable of producing a lightning discharge. By the use of this expression one may formally express the lightning discharge frequency as a function of the net convected current density and the critical dielectric strength of air. In this way one may plot Fig. 17 giving the discharge frequency as a function of the activity index defined as $\rho\overline{V}/\lambda E_c$ [20].

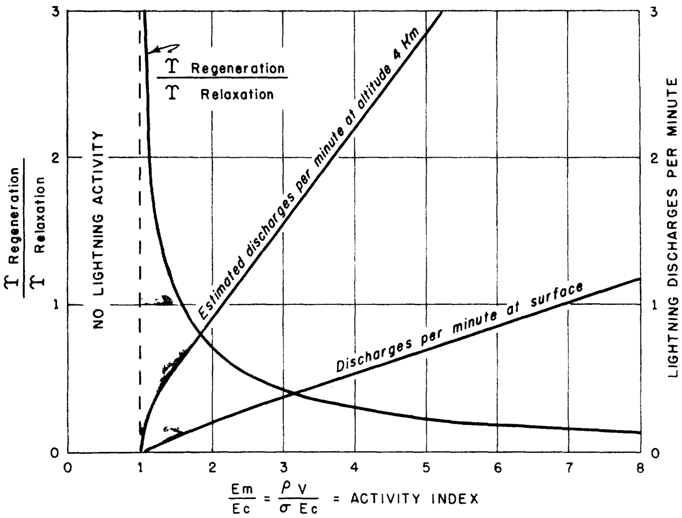

Fig. 17—Estimated relation between the electrical activity index, the lightning recurrence frequency, and the ratio of the regeneration to relaxation times.

For short discharge paths it is well known that the dielectric strength of air is something like 20,000 volt/cm but as the path length increases and electron avalanches develop the dielectric strength steadily decreases to about 4500 volt/cm at ground levels [40]. At higher levels it is systematically less. This value of E_c has been adopted in calculating Fig. 17.

If the atmosphere were a perfect insulator with an extremely high dielectric strength, only selectively charged raindrops would fall, and thus separate free charge until an electric field was established that would either drag downward the lighter particles left overhead or the raindrops would be supported by the field. One may calculate the electric field required to support the droplets and it is found that the required field is in excess of 25,000 volt/cm and greatly exceeds any gradient that can continuously be maintained in ordinary air [18]. This means, in general, that true equilibrium fields seldom fully mature in heavy rain regimes because lightning discharges intervene.

The Initial Electrification of All Precipitating Clouds

The crucial problem of precipitation electricity is to describe how light rain falling from a neutral cloud usually initiates electric fields of from $+10$ to $+30$ volt/cm at the earth's surface. It is true that an all pervading fair weather electric field exists over the earth and presumably has appreciable values at all levels even within a neutral cloud. Therefore, if regenerative mechanisms are invoked to describe the high, subsequently developed fields, this residual field may be of theoretical significance. Actually the presence or absence of a small initial field is not considered important since electric fields may be established in a cloud which is at first entirely neutral and by other straightforward energetic processes.

It is emphasized again that ions are always produced in *pairs* and that the mobility of the negative ion in *clean* air is some 40 per cent larger than that for the positive ion. This provides a fundamental mechanism for establishing a higher conductivity for the negative ions than for the positives, in those regions where suspended particulate matter is a minimum. Observations clearly show that the condensation and sublimation nuclei density normally decreases very rapidly with altitude [35]. Therefore, at rain and snow forming levels, one might anticipate that the number of precipitation particles per unit volume would be low and the negative conductivity would be notably larger than the positive conductivity. This difference has been observed by a number of investigators in clear air and therefore, according to (21), one would expect snow flakes or water droplets at high levels to carry an excess negative free charge.

Now it has been possible to determine the ratio of the positive and negative ionic conductivities from a knowledge of the number of cloud droplets per unit volume, their radius, and the rate of ion pair production. This ratio determines the free charge carried on the droplets through (21). Thus, in the special case when the cloud droplet or snow flake density is low, appreciable net electrification is induced by the difference in ionic conductivities. To illustrate the initial electrification processes, consider an example. Published data on the size of falling snow flakes show that a typical snow flake radius is 0.05 cm and its mass approximates 8×10^{-6} gms [34]. Now when the condensed water content approximates a typical 10^{-6} gm/cm^3, the number of snow flakes per unit volume is 0.12 so that Na approximates 0.006. Thus, at snow forming levels N^2a^2/q approximates 3.6×10^{-6} and by Fig. 15, $\ln \lambda_+/\lambda_- = -0.12$. By use of (21) it is found that the systematic negative charge transferred to the typical snow flakes by ionic diffusion is $Q = -5.2\times10^{-7}$ esu and the specific charge approximates $Q/M = -0.065$ esu/gm. In a similar way one may show that the large rain initiating droplets produced by condensation at levels where the air is relatively free of pollution will produce specific charges of comparable but somewhat larger magnitude. As noted in (26), the *systematic* specific free charge is conserved when the melted or newly formed droplets associate to form larger raindrops. Accordingly, it is evident that, when these droplets coalesce and fall towards the ground, they will transfer negative charge downward. It remains only to determine the magnitude of the electric field that these electrified drops may produce.

By substituting the values suggested in the above paragraph in (21), assuming that liquid or crystalline water content is 10^{-6} gm/cm^3, and that the drops grow large enough to fall at a velocity of 400 cm/sec, then it is found by (33) and (38) that at 2-km altitude where $\lambda = 4.10^{-4}$ esu, that $E_e = +0.06$ statvolt/cm $= +20$ volt/cm. Such an electric field is the same sign and approximate magnitude as the field commonly observed whenever stratus clouds of modest depth precipitate. The field is more than an order of magnitude larger than the fair weather field and is in the direction of commonly observed electric fields in thunderstorms just prior to a discharge. We consider it adequate to excite all the induction and hyperelectrification effects mentioned in the foregoing paragraphs and thus initiate through further regeneration full scale lightning activity.

Electrification of drops by the above process also takes place in the lower levels of the atmosphere but the charges here are predominantly positive because of the excess conductivity of the positive ions. This special case has been considered [26].

Criteria for the Establishment of High Electric Fields by Regeneration

The foregoing section has shown how the diffusion of ions onto falling precipitation may sometimes establish initial electric fields approximating $+20$ volt/cm. Such a field does not depend on the presence of an initial electric field or upon influence effects.

According to (22) and (24), large charges are transferred to raindrops whenever electric fields are present and these charges are proportional to the impressed electric field. It is important to determine whether the charge so produced can maintain or actually increase an initial field of moderate intensity.

Let the charges transferred to rain by the various influence processes considered above be represented by

$$Q = 3BE_0a^2 \text{ esu} \tag{41}$$

where B is a numerical constant of the order of unity which depends upon the specific electrifying process and upon the relative values of the average and maximum charges actually produced. The charge per unit mass, accordingly, is given by

$$\frac{Q}{M} = \frac{9BE_0}{4\pi ad} \text{ esu/gm.} \tag{42}$$

Thus, by (35), (38), and (41) one finds that

$$\frac{E_e}{E_0} = \frac{(\mathrm{LWC})VB\phi\left(\frac{\lambda_+}{\lambda_-}\right)}{4\pi da\lambda} = \frac{9B\left[\phi\left(\frac{\lambda_+}{\lambda_-}\right)\right]P}{4\pi da\lambda} \tag{43}$$

where P is the mass precipitation rate in gm/cm^{2}sec and $\phi(\lambda_+/\lambda_-)$ represents the functional dependence of

(22) or (24) on the conductivity ratio. This function is also dependent upon the drop radius a.

It is clear that if the generated electric field E_e is greater than the electric field E_0 which transfers charge to the raindrops, then the drop charges will increase and the electric field can steadily increase or regenerate until the dielectric strength of air is surpassed. Accordingly, the criterion for the regeneration and establishment of large fields within a thundercloud from a small initial intensity is that (43) be greater than unity, or that

$$\frac{(\mathrm{LWC})V}{\lambda a}\,\phi\left(\frac{\lambda_+}{\lambda_-}\right) = \frac{P\phi(\lambda_+/\lambda_-)}{a\lambda} > \frac{4\pi d}{9B} \doteq 2.8. \quad (44)$$

For the purpose of illustration, it is convenient to adopt numbers that describe the *critical case;* note that precipitation rates and free charges *larger* than this critical value will permit regeneration while lesser values will degenerate. Thus, in this critical case one may adopt as representative $B/d=0.5$, $\phi[\lambda_+/\lambda_-]=0.5$, λ at 2 km $= 4\times10^{-4}$ esu, so that $P=0.0022a$ gm/cm^2 sec. Thus if $a=0.05$ cm corresponding to "medium rain" then $P=0.4$ gm/cm^{2}hr $=0.4$ cm of H_2O/hr. Such precipitation rates and liquid water contents (LWC) are frequently exceeded. It is clear from these figures that regeneration and build up to high electric fields cannot occur unless the precipitation rate exceeds that of typical "medium rain" and unless $\phi[\lambda_+/\lambda_-]$ is some appreciable fraction. The writer believes that this is a proper conclusion because the data clearly show that heavy precipitation is not always accompanied by lightning. It is noteworthy that large precipitation rates act to accentuate any electrical activity already present.

It would be improper to conclude that gross electrification phenomena can only develop through influence effects, but since these are clearly regenerative under certain conditions and are especially energetic we consider them to be of some importance.

The Estimated Electrification in Active Thunderstorms

The foregoing sections have outlined some of the basic electrical phenomena taking place in the earth's lower atmosphere. The differences in conductivities of the positive and negative ions contribute to differential discharge and electrifying processes that ultimately develop free charges on the falling rain. One now considers the over-all behavior and electrical magnitudes within an active thunderstorm.

It has been shown how an initiating positive electric field of about $+20$ volt/cm could be established by light rain falling to the ground. This initial field is capable of being regenerated and built up by influence effects operating on the falling rain. To illustrate the basic processes, one considers two examples of charge transfer and electric field production that are so energetic that they probably play a major role in establishing the observed electrical state. These processes and possibly others frequently act simultaneously so the electrification of a thundercloud as a whole is likely to be complex.

Consider first a vertical prism of unit cross section extending to high levels where snow flakes and ice crystals are formed and fall towards the melting level. At these high levels the suspended contamination is normally small and some systematic electrification due to ionic diffusion will be produced just as suggested previously. However, quite independent of these diffusion processes the snow crystals will frequently collide and separate. When the separation takes place in an electric field we have seen that large charges of opposite sign are produced on the separated snow crystals. For the purpose of estimation suppose that the ice crystals have a radius that is typically 0.05 cm and that they are favorably oriented with respect to an electric field E_0 at the time of their separation. The magnitude of the positive and negative induced charges by (24) is then 8×10^{-3} E_0 esu. Now when this mixture of highly charged ice crystals carrying both positive and negative charges fall to the melting level and are there converted into water droplets *further collisions will result in association* to form a distribution of highly charged *raindrops* related to that shown in Table IV. It is estimated that some 65 associations between such small *melted* ice crystals will take place before they grow into a "medium raindrop" having a radius of 0.05 cm [34]. Thus, by use of (25), one may calculate the mean multiplied drop charge, averaged without respect to sign, as 5.1×10^2 E_0 esu. The specific charge carried by such associated raindrops is 96 E_0 esu/gm. A short calculation will show that the ratio of the electric field at the surface of the drop to the exciting field E_0 is 20. Thus, if the exciting field E_0 is as much as 2 statvolt/cm the field at the drop surface will approximate 12,000 volt/cm. Any additional charge may well induce corona and thereby limit the drop charges. This example suggests that the electrification by induction and their subsequent association will "fully electrify" the produced droplets whenever the original induced electric field much exceeds 2 statvolt/cm. Attention is drawn to the fact that nearly equal numbers of positive and negative drops are produced by this process. However, as this mixture of positive and negative drops falls in the atmosphere the conductivity measurements [7, 37, 39, 43] together with the measurements on the discharge characteristics of our flying laboratory, Fig. 9, show that they will discharge selectively. Thus when the mixture of drops falls some 2 or 3 km an excess free charge is established having a sign corresponding to the ions exhibiting the larger conductivity [27]. At levels above 3 or 5 km the negative ion conductivity is in excess and drops falling through this region would accumulate a negative free charge. Below 3 or 5 km there would be a marked tendency for the drops to accumulate a positive free charge [26]. Now when the ratio of the conductivities λ_+/λ_- approximates

0.9 the differential discharge of the raindrops will establish thereby an excess negative free charge that is transferred toward the earth with a velocity corresponding to the terminal velocity of "medium rain," or 400 cm. Thus when LWC $=10^{-6}$ gm/cm^3 one may calculate the convected current density by (34) and it is found to approximate $7\times10^{-4} E_0$ esu/cm^2. The reader may verify that such a current density summed up over the entire area of a typical thunderstorm will establish a total convection current of more than one ampere if $E_0=2$ statvolt/cm. Such a current approximates the measured currents [7].

One may estimate from (38) the equilibrium electric field that will be established as a result of the convected charge moving towards the ground. At a selected height of 2 km one may adopt a conductivity for clear air of 4×10^{-4} esu or 4×10^{-5} esu within a typical stable cloud. Thus by (38) the established equilibrium electric field would approximate 1000 volt/cm in clear air or 10,000 volt/cm within a cloud. Because of uncertainties in the conductivity and the physical properties of the falling rain exact numerical values are unimportant, but one may notice that the charge transferring processes are adequate 1) to regenerate the initial field and 2) to establish electric fields and gross currents within the thunderstorm that are descriptive of the available observations. Whenever the electric field exceeds about 4500 volt/cm at the earth's surface or something less than this value over an extensive path, observations show rather clearly that a disruptive lightning discharge will be initiated [40]. Accordingly, one may understand in quantitative terms one of the basic mechanisms that is capable of establishing lightning.

Consider another energetic mechanism of somewhat different type and suppose that some free charge already exists within the thundercloud. We have seen that hyperelectrification is important at the boundary of discontinuity between the thundercloud and the clear air outside. This mechanism has been discussed in some detail [29] and leads to drop charges of magnitude given by (22). According to this expression, high charges all of one sign are transferred to the raindrops in the transition layer. To illustrate the process, assume that the precipitation is characterized by "medium rain" and the drop radii approximate 0.05 cm. Thus, the charge on each drop by (22) is $7.5\times10^{-3} E_0$ esu. When E_0 is large enough the drops may again carry charges comparable to the maximum as discussed previously. Further assuming that the liquid water content is a typical 10^{-6} gm/cm^3, the space charge density will be $1.5\times10^{-5} E_0$ esu/cm^3 and this falls towards the earth at the velocity of fall for "medium rain." Therefore, the convected current density is $6\times10^{-3} E_0$ esu/cm^2 and the total current for a typical thunderstorm may be several amperes. The precipitation charge in the above example is all of one sign and could have been calculated directly from (33). Again noticing that the equilibrium electric field is determined by the convected current density and the conductivity one may again substitute the conductivity at 2 km or 4×10^{-4} esu to show that the equilibrium field is 15 E_0 statvolt/cm or 4500 E_0 volt/cm. Thus if E_0 has typical values the falling rain is capable of establishing an electric field, even in clear air, which is greater than the dielectric strength of air. Further, one may notice that if a lower conductivity, characteristic of stable clouds, is employed the equilibrium field would be much larger than that just calculated and the field would then far exceed the dielectric strength of air. In any event, lightning is likely to intervene, which will equalize the separated charges.

The above electrification processes are exceedingly energetic and are thought to be principally responsible for the observed separation of free charge in a thunderstorm. It is important to recognize that the sign of the charges produced by hyperelectrification depends on the direction of the electric field at the cloud boundary. When the cloud boundary sees positive charge within the cloud the drops are likely to be negatively charged but if the boundary sees negative charge within the cloud the drops will be positively electrified. It is clear, therefore, that some thunderstorm regions will be characterized by highly charged drops of one sign while other regions will contain highly charged drops of the opposite sign, just as Fig. 6 and our other aircraft measurements clearly show [17]. These aircraft measurements show that negative charges normally predominate on precipitation at the high rain forming levels. The excessive negative ionic conductivity commonly observed at such levels where the suspended pollution is a minimum suggests strongly that perhaps most of the marked sign selective processes considered in the foregoing sections may be fundamentally traceable to the superior mobility of the negative ion. This general view has influenced the interpretation of atmospheric electric problems since the classical measurements of ionic mobilities were first made in 1900 by Dr. John Zeleny.

Relation of Thunderstorm Electricity to the Earth's Fair Weather Field and to the Cleanliness of the Earth's Atmosphere

It is well known that the surface of the earth in all fair weather regions carries a negative charge of about 4×10^{-4} esu/cm^2, and that this maintains an inward electric field of about 1.5 volt/cm. Wilson suggested long ago [45] that the maintenance of the observed fair weather charge and field was probably related to the presence of thunderstorms somewhere else on the earth. Probably most workers in the field of atmospheric electricity accept this explanation as correct because there are worldwide fluctuations of the fair weather field which appear to be in phase with the abundance of thunderstorms averaged over the earth. Gish and Wait [7] have estimated the current at the top of a thundercloud where the current density measurements were not complicated by the convective transport of charge on rain, and they found currents approximating 1 ampere per thunderstorm. Since the current to the high atmosphere and the ground must be continuous a negative current of similar magnitude usually flows towards the ground just as we have estimated in the foregoing section. However, because of the relatively high resistance of these lower layers the transfer of charge across this layer is frequently augmented by lightning discharge. We have seen that typically 17 coulombs is transferred to the earth by each lightning discharge. This transfer is frequently supplemented by conduction currents and the charges on the falling rain so that the determination of exact quantities is rather difficult.

We have evidence suggesting that the transfer of charge from the clouds to the earth takes place with greater ease in mountainous regions because such mountains frequently extend well into the conducting atmosphere at high levels. The total currents transferred in mountainous regions is unknown but preliminary measurements suggest that it may be large and the matter deserves careful investigation. The general character of the equivalent electrical circuit in the atmosphere is outlined in Fig. 18.

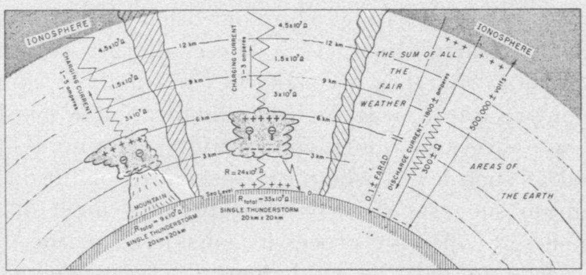

Fig. 18—Equivalent electrical circuit of the atmosphere. From 1000 to 2000 thunderstorms in constant operation are required to maintain the currents in the fair weather areas of the earth. Notice that charged raindrops transport the free charge through the cloud and provide the energy to establish the current.

One aspect of the maintenance of the earth's charge requires special consideration. Fig. 1 shows that in active thunderstorms the impressed electric field is more or less alternating in character and positive and negative fields are common. We have seen that space charge always accumulates in the lower atmosphere which is opposite in sign to the charge on the earth. An analysis shows that whenever time is available to accumulate space charge a positively charged surface will discharge more rapidly than a negatively charged surface. Thus, alternating electric fields impressed on the lower atmosphere will result in the transfer of more negative charge to the earth than positive. That is to say, the lower atmosphere has rectifying properties [9]. Even if the acting charge separating processes in the atmosphere were purely random in nature, it is clear that this earthly condenser would accumulate and maintain a negative charge. The magnitude of the rectified current would not fully account for the observed field unless thunderstorms are more general and cover more area than we now believe [9].

The fundamental importance of thunderstorm activity and the maintenance of the earth's fair weather electric field has never been adequately emphasized. It is clear that it plays no direct part in the over-all weather process but its secondary role in sweeping the atmosphere clear of fine particulate matter can hardly be overestimated. It is well known that the number of condensation nuclei decrease rather rapidly with increasing altitude and this has generally been attributed to gravitational fallout. With the advent of nuclear bombs the problem of cleansing the stratosphere of its suspended particulate matter is a very practical one. One may easily show that a particle of radius 10^{-6} cm and carrying one elementary charge will experience a force, produced by the fair weather electric field in the stratosphere, that is roughly ten times as large as the gravitational force. Near thunderclouds the relative forces will be proportionately much greater. Accordingly, in the presence of clouds, or indeed in clear air, the superimposed systematic electrical motions communicated to the particles acts to precipitate out the very fine particles onto cloud droplets and on the ground. We do not suggest that the mechanism is important for particles as large as a micron because here gravity plays probably the major role but it is extremely difficult to understand how the tremendous numbers of very fine particles of the size of many condensation nuclei suspended in the atmosphere are purged unless electrical phenomena are invoked. Accordingly, this author believes that the role of thunderstorm electricity is an important one in making this earth a habitable abode for man.

Conclusion

The foregoing sections have summarized probably the most important phenomena responsible for the electrification of precipitation and thunderstorms. We have attempted to emphasize that thunderstorm electrification is but an extreme manifestation of the charges commonly produced on all precipitation. It seems clear from the data that large, newly formed raindrops are usually electrified but do not always produce lightning. Thus, one infers that there are secondary relationships related to the rate of precipitation and to the character of the cloud development which somewhat determine the electrical activity of the cloud. These relationships are specified by (44).

According to the above analysis the electrification is principally associated with: 1) Droplets or ice crystals formed in clean air at high levels. The process here is primarily one of selective diffusion. 2) Special phenomena in the transition layer between a cloud and its clear air environment. In this layer, ions of a single sign from outside the cloud, are commonly concentrated and are deposited on cloud droplets and raindrops by hyperelectrification. 3) Electrical induction by the contact and separation of ice crystals or raindrops exposed to an electric field. The mechanism is such as to produce a mixture of positive and negative drops carrying roughly the same charge magnitudes. 4) The selective discharge of mixtures of positive and negative drops as they fall down through an environment wherein the positive and negative conductivities are different. All of these processes are energetically capable of contributing to the over-all electrification of a thundercloud. Some of these processes are evident in light rain and drizzle formed at low levels which is known to be weakly electrified [26].

It seems clear from the analysis that rapid regeneration and build up of the electric field accompanied by frequent lightning discharges can hardly be anticipated unless the precipitation rate *exceeds* that characteristic of "medium rain." All of these requirements appear consistent with the available knowledge on the meteorological characteristics of thunderstorms. Thus, the above quantitative description of thunderstorms is adequate to account not only for active thunderclouds extending to high freezing levels, but also in very clean air when the storm cloud fully develops below the freezing level. Moreover, the description does not require that lightning be produced by every heavily precipitating cloud. This summary attempts to discuss only the outstanding features of thunderstorms and because of their complexity exceptions must be anticipated.

Many of the processes which we have examined in this communication are directly applicable to the generation of volcanic lightning. The main requirement is that particulate matter collide, separate, and fall in a semiconducting ionized atmosphere. It is anticipated that lightning storms much like those observed on the earth will develop on other planets or on stars.

The analysis of atmospheric electric phenomena in precipitating regions has necessarily ignored a number of processes that have been considered adequately by other writers. Our research team has examined a number of suggested electrifying processes to determine roughly their relative importance in atmospheric electricity. Some of these processes doubtless contribute to the overall electrification under especially favorable conditions. But the mechanisms we have considered above all prove to be energetic and electrically active in the laboratory. Much more work needs to be done in this field of research and there is a large number of stimulating problems yet to be solved. This review is intended to emphasize those mechanisms that appear to the writer to be most important and to stimulate further work in this specialized area of basic physics.

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An Improved High-Gain Panel Light Amplifier*

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***Summary*—A grooved photoconductor light-amplifying picture panel is described, whose gain is more than 10 times greater than any previous amplifier and whose threshold for input light is reduced. These improvements have been obtained with a new electrode structure which enables a more efficient type of operation and by the use of a more sensitive photoconductive powder. Measured input-output characteristics are shown comparing the new and earlier types of operation and also indicating the effects of different supply frequencies. The time-integrated energy gain for a one-second excitation is of the order of 100 with input light of the same spectral distribution as the output. The asymptotic energy gain after a longer excitation interval is about 800 with optimum spectral matching of the photoconductor. Although the decay time is of the order of seconds, as with early amplifiers, the shape of the decay curves and the rate of decay are changed by the new method of operation.**

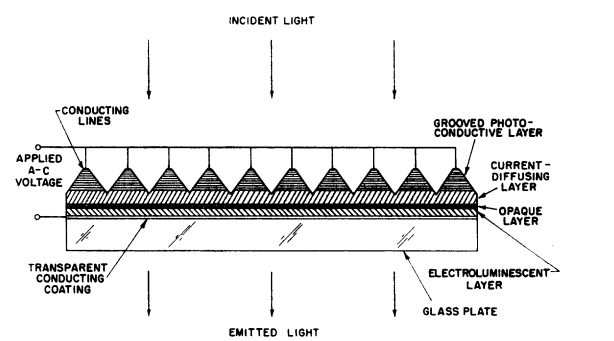

Fig. 1—Basic design of grooved photoconductor light amplifier.

Introduction

THE basic design of the original panel light amplifier[1] is shown in cross section in Fig. 1. The principal layers are the electroluminescent phosphor layer which produces the output image and the photoconductive layer which varies its resistance in accordance with the input radiation. Since the photoconductive layer in the dark must be many times higher in impedance than the electroluminescent layer, it is made much thicker. To efficiently illuminate the thick photoconductor, it is grooved. In operation, the incident light is absorbed on the surfaces of the photoconductor so that photocurrents flow down the sides of the ridges and converge at the bottom of the grooves. To efficiently utilize the entire phosphor area, a resistive current-diffusing layer is placed below the photoconductor. This spreads the photocurrents slightly, approximately one groove width. To prevent feedback of output light, an opaque insulating layer is provided on the back surface of the phosphor layer.

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