effects in the thermal region makes the determination of the $1/v$ slope impractical. The region above 2.2 ev was next studied using good resolution as shown in Fig. 15. This shows a small dip near 90 ev. The region above 50 ev was then studied using maximum resolution as shown in Fig. 16. This shows a dip near 95 ev which may be multiple in view of the shape of the dip. If it is because of a single level at 95 ev then $\sigma_0\Gamma^2 \sim 800$. The rise in transmission above 10,000 ev probably indicates a decrease in the scattering cross section at higher energies. There are five stable isotopes in germanium. The three well established activities[12] induced in germanium by (n, γ) reactions are 40 hr. Ge^{71}, 89 min. Ge^{75}, and 12 hr. Ge^{77}.

We take pleasure in acknowledging our indebtedness to Professor J. R. Dunning for his valuable suggestions and stimulating discussions. We wish to thank Miss Miriam Levin, who assisted with the numerous calculations involved in this paper, and the other members of the cyclotron staff who aided with these measurements.

---

[12] Sagane, Phys. Rev. **55**, 31 (1939); Sagane, Miyamoto, and Ikawa, Phys. Rev. **59**, 904 (1941).

PHYSICAL REVIEW VOLUME 71, NUMBER 3 FEBRUARY 1, 1947

The Electrical Charge on Precipitation at Various Altitudes and Its Relation to Thunderstorms

Ross Gunn
Army-Navy Atmospheric Electricity Project, Naval Research Laboratory, Washington, D. C.

(Received November 7, 1946)

The free electrical charges on individual precipitation particles were measured at various altitudes up to 26,000 feet by an induction method that avoided touching them. In a weak cold front exhibiting no thunderstorm activity, and having the freezing level at 11,000 feet, positive charges averaging 0.033 e.s.u. were observed from 10,000 to 26,000 feet. Negative charges averaging 0.04 e.s.u. were measured from the surface up to 20,000 feet. Positive charges were not observed below 10,000 feet and negative ones were not detected above 20,000 feet. Between these levels a mixture existed. The free charge on a large number of the particles was so great that the electric field at their surface was an appreciable fraction of the breakdown field for air, showing that powerful electrifying agencies exist even under rather quiet frontal conditions. Electric field measurements on the airplane showed that the particle charges were largely neutralized by nearby charges, presumably on the air or on the tiny cloud droplets. It is shown that the removal of this neutralizing charge will immediately produce thunderstorm electric fields and potentials. A time plot of the electric field on the surface of a flying airplane during the interval of a lightning strike is given.

Although it has been two centuries since Benjamin Franklin flew his kite to demonstrate the electrical character of lightning, little real progress has been made in the fundamental understanding of the electrical charge generating and transferring processes in thunderclouds. Because every lightning discharge in a cloud profoundly changes the electrical state within it, surveys of the cloud capable of detailed interpretation must be completed in a time short compared to the charging time. This means that an active thunderhead must be explored in something less than 10 seconds or, if a longer time is necessary, a steady state cloud must be chosen in which the convective activity is so low that disruptive electrical discharge does not take place. The Army-Navy Atmospheric Electricity Research Project has had assigned to it a Flying Fortress that has been instrumented to investigate the electrical state of the lower atmosphere. This airplane has flown through almost every conceivable type of weather during the past two years to determine the character and magnitude of the electrical effects associated with cloud and storm formations.[1]

---

[1] Gunn, Hall, and Kinzer, "The Precipitation-Static Interference Problem and Methods for its Investigation," Proc. Inst. Rad. Eng. **34**, 156P April (1946).

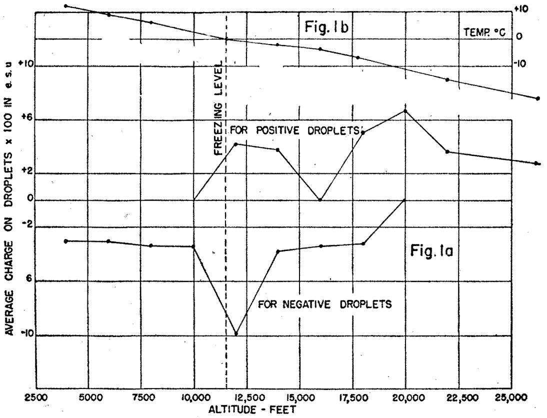

FIG. 1. (a) Average electrostatic charge on precipitation particles at various altitudes: (b) Corrected temperature as measured with MI313 aircraft psychrometer.

The present paper is concerned with the electrical characteristics of precipitation falling within a weak cold front. The observed changes in altitude and speed of the airplane flying through and at right angles to this front showed that there was negligible convective activity. Further, the electrical fields resulting from such activity were measured and found to be small. The observations showed, too, that measurable electrical charges were carried by the precipitation and that these charges, through appropriate mechanical separation, were sufficiently large to produce high electrical potentials and lightning. Measurements taken in active thunderstorm areas show that the charge per droplet (or flake) may be as much as an order of magnitude greater than those encountered in a mild cold front. Because of the stability of the front employed in this investigation, measurements made therein are considered more significant than would be the case if lightning discharges were present that suddenly might change the whole electrical configuration of the storm area.

The weather of the present investigation was a weak occluded front of the cold type accompanied with a low pressure trough oriented North-South, that moved eastward across Minnesota on July 27, 1945. As the front progressed, it became more of a cold front in character. Steady rain appeared over northern Minnesota. The project airplane flew through the front again and again at various altitudes and at right angles to the direction of the front collecting pertinent meteorological and electrical data. In addition to the usual flight instruments and precision meteorological thermometers, the airplane was equipped with two important specialized instruments designed to measure the electric field at the surface of the airplane and the electrical charge resident on the droplets of the encountered precipitation.

The electric field meters[2,3] are induction devices consisting of a highly insulated electrode exposed outside the airplane to the electric field and connected to the grid of a vacuum tube. The exposed electrode is arranged to be alternately exposed and shielded by a grounded metallic rotor driven by a small motor. In the presence of an electric field, an alternating voltage is produced on the grid of the vacuum tube that is proportional to the field. The output from the first vacuum tube is passed through an amplifier and thence to a direct current meter by way of a mechanical rectifier driven in synchronism with the grounded metallic rotor. Since such a system is phase sensitive, the indicating meter reads not only the magnitude of the electric field but also its direction. The electric field meters are mounted both on the top and on the bottom of the fuselage in such a way that it is possible to determine the probable origin of any measured electric field. These devices have been invaluable in the assessment of data and in determining the electrical state of the atmosphere.[4]

Some years ago the pioneer results of Gschwend,[5] who simultaneously measured the electrical charge and size of individual raindrops, were reinvestigated by a new method. Two highly insulated inducing rings separated vertically by 75 centimeters were mounted below a suitable collimator and connected to a high gain amplifier, the output of which was connected to a recording oscillograph. Raindrops falling through the two rings induced two successive deflections of the oscillograph, the amplitude of which determined the sign and magnitude of the

---

[2] R. Gunn, Phys. Rev. **40**, 307 (1932).

[3] Waddel, Drutowski, and Blatt, Proc. Inst. Rad. Eng. **34**, 161P April (1946).

[4] Stimmel, Rogers, Waterfall, and Gunn, Proc. Inst. Rad. Eng. **34**, 167P April (1946).

[5] Gschwend, Jahrb. Radioakt. u. Electronik. **17**, 62, 192 (1921).

charge on the raindrop, and the time interval between the two deflections measured the time it took the drop to fall the distance between the two inducing rings. Thus, the charge magnitude, sign, and the velocity of fall (or droplet size) could be simultaneously determined. This method has now been adapted for use on aircraft with considerable success.

A truncated sheet-metal cone is mounted on the airplane with the smallest circular opening of 9.62 cm^2 area presented face forward in such a way that precipitation coming through this opening will not touch the inner sides of the cone. Thence the particles move outward from the big end of the cone without being broken up or disturbed in any way. Inside the cone are mounted two inducing rings; the forward one is 5 centimeters in diameter and 5 centimeters long, while the aft ring is 12 centimeters in diameter and 5 centimeters long. The forward ring is highly insulated and connected through appropriate wires and shields to a pressurized cathode ray oscillograph equipped with a slow speed motion picture camera. The aft ring in the wider part of the cone acts as an electrostatic shield and is grounded to the cone and to the frame of the aircraft. The whole assembly is mounted on a streamlined strut 45 centimeters below the fuselage where it is moderately well shielded electrically from the moving propellers and from sharp points that might break into corona. It is found with such a device that very few precipitation particles ever hit the inducing ring and that it is easy to maintain the necessary high insulation even in the heaviest rain. Raindrops striking the leading edge of the cone and breaking up produce charges in which the figures of the pulses impressed on the oscillograph are notably different from a charged droplet proceeding through the inducing ring in a normal manner. Thus, it is possible to discard all traces except those caused by droplets that have traversed the apparatus without touching it. The output from the inducing ring is fed into a standard high sensitivity amplifier and then to a pressurized cathode ray oscillograph. A 35-millimeter movie camera is arranged to take pictures of each single sweep. The oscillograph in general is calibrated by employing standard a.c. voltages whose amplitudes are periodically photographed on a calibration frame. The calibrations for electrical quantity and for the capacity of the complete system were determined by using a small air gun and putting charges of various magnitudes on the shot fired therefrom. These charges on the shot were measured after traversing the inducing ring by being captured in a Faraday cage connected to an electrometer. Supplementing this information with a knowledge of the voltage sensitivity corresponding to any given setting of the amplifiers and the capacitance (which was 357 centimeters), the quantity sensitivity is easily checked in flight. The time of sweep per traverse of the oscillograph was usually 0.169 second. The scale of the measuring equipment and sweep rate were selected so that each sweep usually contained from 3 to 10 impulses whose magnitude and direction determined the charge on each individual droplet traversing the inducing ring.

Coherent sets of data were obtained using the above apparatus for the mild cold front described in an earlier paragraph and at various altitudes. It may be seen from Fig. 1a that electrical charges reside on the precipitation at all altitudes from the highest observed at 26,000 feet on down to the ground. In this investigated front, the charge on the precipitation at high altitudes is positive in character while at low altitudes the

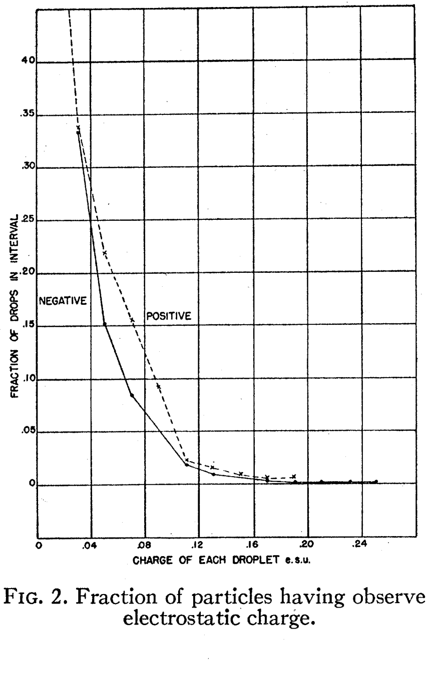

FIG. 2. Fraction of particles having observed electrostatic charge.

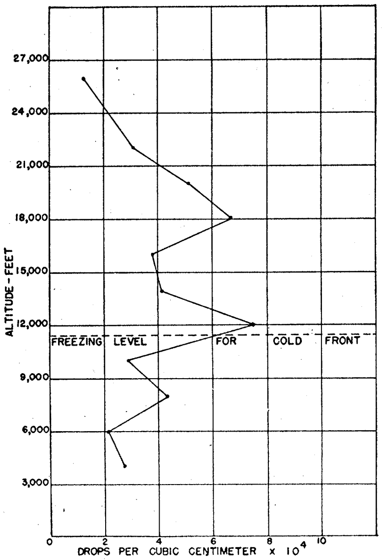

FIG. 3. Vertical distribution of the number of charged particles per unit volume.

charge on the particles was negative. However, at intermediate altitudes, for example from 20,000 feet on down to 10,000 feet, a mixture of positive and negative droplets was encountered. At 16,000 feet no positive droplets were measured, but at 14,000 feet a few and at 12,000 feet quite a number were observed. However, at lower altitudes, only negatively charged particles were encountered. The average electrical charge on some 500 positive droplets above 10,000 feet altitude approximated 0.033 electrostatic unit. The average negative charge on about 700 particles at altitudes below 20,000 feet was somewhat greater and approximated 0.04 electrostatic unit. Figure 1a shows plainly the distribution of charge on precipitation at various altitudes both for the positive and negative particles. It is thought to be of considerable theoretical importance that the freezing level is at approximately 11,000 feet and is below the general area of maximum electrification of the particles. The corrected temperatures as determined from a precision ML313 aircraft psychrometer mounted outside the fuselage are plotted in Fig. 1b. The accuracy of such temperature measurements, in common with all such measurements on aircraft, is subject to some uncertainty.

The number of droplets measured at any one altitude was hardly sufficient to permit a statistical determination of their free electrical charge, but the average over the whole storm is probably significant. In Fig. 2 the measured electrostatic charge on the intercepted droplets is plotted against the fraction of the droplets in any charge range. It may be seen that a large number of the droplets (or snow flakes) carry charges less than 0.02 e.s.u. and that the number carrying charges larger than 0.1 e.s.u. is relatively small. The difference in distribution between the positive and negative particles is not thought to be significant.

The reason why the charges on the particles seldom exceed 0.1 e.s.u. is easily understood. If a particle, for example, is assumed to be typical of "medium rain," then its radius[6] approximates 5×10^{-2} centimeter, and the electric field at its surface for a total charge of 0.1 e.s.u. is at least as great as 12,000 volts/centimeter. This value approximates the dielectric strength of air. It seems probable, therefore, that the particle electrification processes even in a quiet frontal rain area are so potent that typical droplets carry an appreciable fraction of the largest charge possible in an ordinary atmosphere. Since the dielectric strength of air is proportional to the pressure, the charge limitation imposed by corona discharge plays a relatively larger part at high altitudes than it does at the earth's surface. It is worth re-emphasizing that these charges were measured in a weak cold front that showed little evidence of important thunderstorm or electrical activity.

It has also been found possible to determine the density or the number of appreciably charged droplets per unit volume while flying through normal precipitation. It should be clear that with a known cross-sectional area exposed ahead of the inducing ring and with known values for the corrected air speed of the airplane, it is possible to determine the volume of air swept out per unit time by the opening in the cone. With values of this volume and the length of time that a given number of impulses are measured or observed on the oscillograph, it is possible to determine the number of charged drops swept up per unit volume. It is recognized that this procedure will not measure the number of tiny

---

[6] R. Gunn, "Electricity of Rain and Thunderstorm," Terr. Mag. Atmos. Elec. 40, 79–106 (1935).

droplets which bear very small charges, but these are of small importance in transporting water out of the cloud. In reducing the data, the number of impulses measured on the oscillograph was determined for every frame taken and the time of sweep for each frame noted. In Fig. 3 is given a plot of the number of charged precipitation particles per cubic centimeter as a function of the altitude above the ground. It should be emphasized that the number of drops per cubic centimeter is the number of drops with sufficient charge on them to produce a noticeable deflection on the oscillograph, or greater than about 0.01 e.s.u. Some drops were undoubtedly overlooked. It is interesting to notice that at 26,000 feet the number of drops per cubic meter is only about 130, and the number increases more or less irregularly as the altitude decreases to about 12,000 feet. At this level, which is near the freezing level, the number of particles per cubic meter approximates 750 and is a maximum. Below the freezing level, the density decreases rather rapidly to much smaller values. This seems to be of interest in interpreting the possible modes of formation of rain because if every raindrop in the lower atmosphere is assumed to come from a melting snow, or water and ice particle, as Bergeron has suggested,[7] it seems obvious that there should be more particles per unit volume at the freezing level than there would be raindrops below. This is because the raindrops will usually fall at a greater speed than the snow, or the water and ice particles, and therefore there should be a maximum in droplet density at the melting level. Our meager data suggest that this maximum may be real. A series of similar measurements in an active thunderstorm gave essentially similar results.

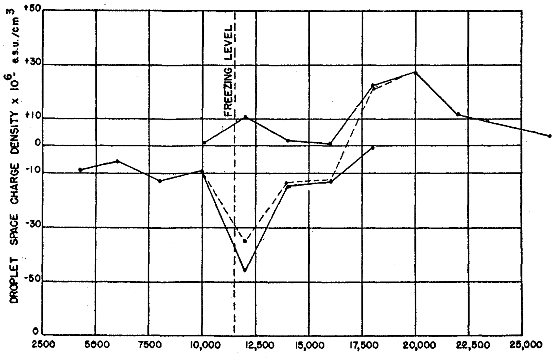

FIG. 4. Vertical distribution of particle space charge density.

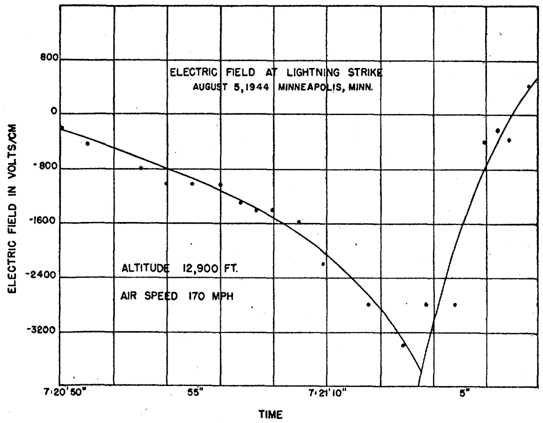

FIG. 5. Measured electric fields on B-25 before and after lightning strike, August 15, 1944, 13,000 feet.

It should be evident from the foregoing discussion that with a knowledge of the charge on the precipitation particles and the number of particles per unit volume, one may calculate the particle space charge. Values of the particle space charge are plotted in Fig. 4 both for the positive and negative particles (solid line) and for the net particle space charge (broken line). Particle space charge must be clearly differentiated from the true space charge because neutralizing charges always surround rain droplets, and these must be counted in evaluating the true space charge. That neutralizing charges exist somewhere outside of each droplet in the cold front was well demonstrated by the fact that the measured electric fields throughout the area were, in every case, orders of magnitude smaller than one would calculate from the free charges actually resident on the precipitation. In this connection it is well to remind the reader that if the region of the free charge distribution is large compared to the vertical height above the ground, then the vertical electric field E is given nearly enough by

$$E = 4\pi \int \rho dz + E_0 \tag{1}$$

where ρ is the true space charge density; E_0 is the originally existing field produced by surface

---

[7] "On the Physics of Cloud and Precipitation," Meteor. (Union Geodesique et Geophysique Internationale, Lisbon, 1933) pp. 156–170.

distributions of free charge; and z is the vertical coordinate. Since E_0 is usually negligible, $E/4\pi$ as measured on the airplane gives the value of the free charge integrated throughout a prism of unit area and extending vertically through the front.

The particle space charge is considered to be of great importance because, if relative motion is brought about by any means whatever between the particles themselves and the air or cloud droplets in which they are immersed, and if there is a separation of the two, then free charge will appear in the adjacent area. In the presence of adequate air currents, this surplus charge may obviously be some appreciable fraction of the space charge appearing on the particles alone. If the free space charge distribution is known, then the electric field and the potential distribution may be immediately calculated by standard electrostatic procedures. If it is assumed that the free space charge is equal to the space charge on the precipitation and that no compensating charge exists on the air outside the droplets, it is easy to calculate, using the observed particle space charge density shown in Fig. 4, that in a cloud area in which vertical convection takes place, that electric fields up to 20,000 volts per centimeter and potentials up to 10^{10} volts may immediately be produced. A calculation of this nature has been given in an earlier paper.[6] These calculated electric fields and potentials are an order of magnitude greater than those required for a lightning discharge and thus show that a partial separation of the charge is adequate to produce observed thunderstorm electrical effects. For example, in our B-25 experimental airplane, on August 15, 1944, we flew through an active thundercloud and were struck by lightning. An electric field indicator mounted on the belly of the plane[3] near the trailing edge of the main wing provided values of the electric field both before and after the strike even though some of our other measuring equipment was destroyed by the bolt. The strike occurred at about 13,000 feet. The electric field increased as shown in Fig. 5 to a value of about 3400 volts per centimeter in about ten seconds and recovered in three seconds. These measured values of electric field must be corrected for distortion due to the presence of the airplane in the thunder cloud. Other measurements show that if the electric field at the time of the strike was approximately vertical, then the correction for distortion was such that the electric field existing in areas away from the plane and at 13,000 feet, closely approximated 1600 volts per centimeter just prior to the stroke. Thus, making a reasonable estimate of the dimensions of the cloud, one is led to the conclusion that the measured values of electric field and potential are smaller by perhaps an order of magnitude than the values which would be produced if all the charge on the precipitation and that outside of it were suddenly separated by a distance equal to the dimensions of a typical cloud.

The significance of these results in relation to thunderstorm electricity is obvious. The measures show that in a mild cold front, there is a definite tendency for positive electricity to reside on the precipitation at high altitudes; whereas, at relatively low altitudes, there is a marked tendency for a negative charge to exist on the precipitation. Further, simultaneous measures of the electric field show that the integrated true space charge at all levels is small and neutralizing charges outside the precipitation usually exist. Clearly therefore, if vertical air currents separate the associated neutralizing positive and negative charges to any appreciable extent, large electric fields and voltages sufficiently high to cause lightning will be produced. That a redistribution of electric charge will be produced in the event of active vertical air currents can hardly be doubted.

Our data lead to the conclusion that even rain clouds are intrinsically able to produce lightning, and only mechanical effects are needed in an ordinary rainstorm to separate the already existing charge in the cloud from that on the associated precipitation.

The reasons why positive electrical charge predominates on precipitation at high altitudes and negative at relatively lower altitudes are still controversial. We are continuing our measurements on the charges measured in flight on precipitation, and it is believed that as further data become available, we may have, finally, a first-class clue as to the origin of this charging.

The author is glad to acknowledge the assistance of Franklin E. Waterfall in securing much of the presented data.