ELECTRICITY AND RAIN

Why do the positive and negative charges separate in thunderclouds? What happens in the period between lightning flashes? How is air trapped in hailstones?

J. DOYNE SARTOR

THE GENERATION OF ELECTRICITY and the formation of rain in thunderstorms are closely related through the physical and electrical interactions among colliding cloud particles, raindrops and hail. Our understanding of these processes started with the observations of Benjamin Franklin and Lord Rayleigh, in the 18th and 19th centuries, that electric fields exist in thunderclouds and that charged raindrops can coalesce. Modern theories indicate that different fall velocities of large and small drops are responsible for the separation of charge in the interior of the cloud.

Our work at the National Center for Atmospheric Research has included studies of sparking between charged drops and theoretical and experimental investigation of field growth in thunderclouds during the intervals between lightning flashes. We have also looked at drops in bouncing collisions with each other, where we see the trapping of air bubbles (important in the formation of hail) and, in some circumstances, the production of small satellite drops that may act as new centers for raindrop growth and so accelerate precipitation.

Franklin and Rayleigh

During his studies of electricity, Franklin discovered that lightning is an electrical phenomenon, but his investigations of electricity and clouds did not stop with this famous discovery. For example he found that the strong electric fields from thunderstorms can be detected miles away, and he devised a simple warning device for their approach. He connected a wire from the roof of his house to one of two small bells that were free to move and separated by a small distance. The second bell he connected to ground. The bells, attracted to each other by the opposite charge induced on their surfaces by the eleotric field of the approaching thunderstorm, tinkled continuously as they touched, discharged, separated and were charged again by the field. By comparing the charge induced on the end of his wire with charged objects of known sign, Franklin also concluded that clouds passing over his house usually contained an excess of negative charge at their bases.

Franklin, when he lived in the Boston area, noticed that when it rained the lower clouds usually moved in from the east while an upper layer of clouds visible through breaks in the lower layer moved from the west or southwest. Putting these meteorologically astute observations together with his observations of cloud polarity, he proposed a theory of precipitation involving the electrostatic attraction of oppositely charged clouds. He suggested that water vapor derived from evaporation of sea water formed negatively charged droplets and that water vapor from the evaporation of water in the soil produced positively charged droplets. When the lower, negatively charged clouds moving in from the ocean met with the higher, positively charged clouds from the land, the mutual electrostatic attraction among oppositely charged drops caused their coalescence and, therefore, the formation of rain.

The observation that positive charge is usually found above negative charge in rainclouds has been confirmed (or "rediscovered") many times. Franklin's observations of cloud motion agree with data from modern upper-air soundings over New England. His suggestion that water vapor from land and sea carry opposite signs has, however, not been con-

J. Doyne Sartor worked for the US Weather Bureau and the Naval Research Laboratory after taking his BA at UCLA in 1947. He then took masters' degrees at Cal Tech and MIT while with the US Air Force. In 1956 he joined the Rand Corporation, and in 1962 he moved to the National Center for Atmospheric Research, Boulder, Colo. as a program scientist.

firmed (nor has it been specifically tested).

Lord Rayleigh[1] showed in the laboratory that uncharged water drops bounce without coalescing when they collide in an environment shielded from electric fields. In an electric field, or when the drops are charged, the colliding drops readily coalesce. Commenting on the application of his laboratory results to the atmosphere he wrote: "It is obvious that the formation of rain must depend materially upon the consequences of encounters between cloud particles," and "We have every reason to suppose that the results of an encounter will be different according to the electrical condition of the particles, and we may thus anticipate an explanation of the remarkable but hitherto mysterious connexion between rain and electrical manifestations."

Theories of electrification

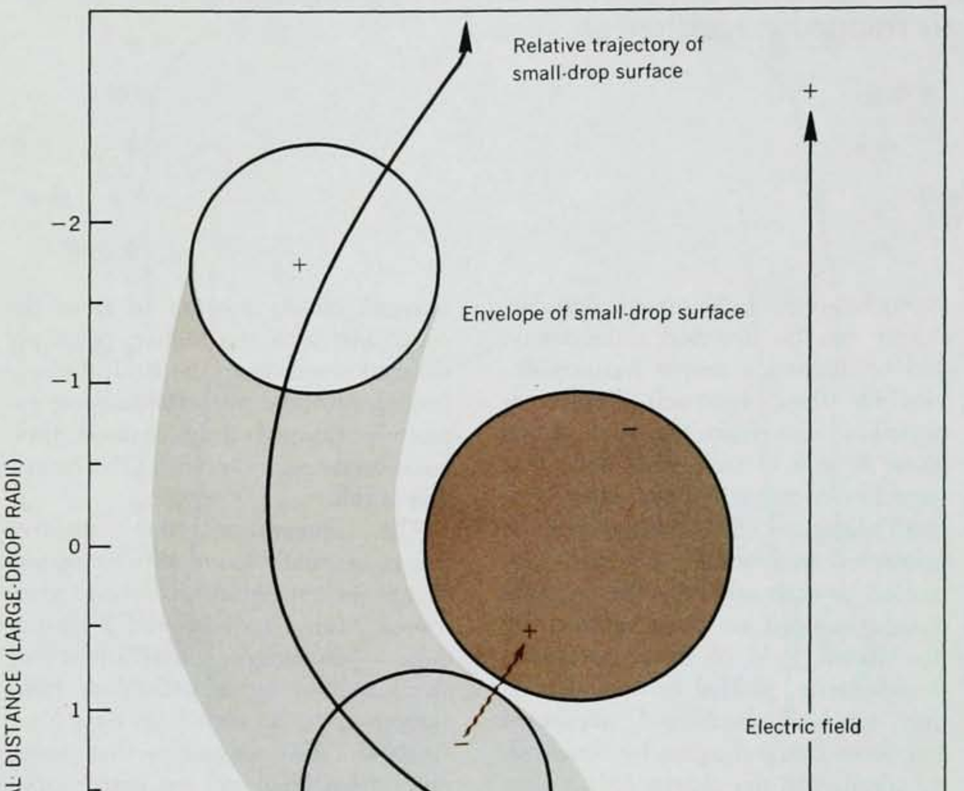
Since these early observations many theories have been proposed to explain the electrification of clouds. Charles T. R. Wilson[2] proposed the theory, in vogue in the first half of this century, that large drops are polarized by the universal electric field of the cloud; because of the aerodynamic motion of the air around them, they selectively capture negative atmospheric ions on the lower surface of each drop. We know now that the supply of atmospheric ions and the initial field are inadequate to substantiate this theory as a basic electrification mechanism. It is, however, generally accepted as a partial explanation of the sign of charge on raindrops reaching the surface in the electrical environment of mature thunderstorms after the electrification has been provided by other unspecified processes.

It is commonly observed that maximal electrification in a thunderstorm takes place near the 0°C isotherm. Therefore many modern theories (for example, those of John Latham and Basil J. Mason,[3] S. E. Reynolds, Marx Brook and Mary Foulks Gourley,[4] and Peter V. Hobbs and D. A. Burrows[5]) concentrate on charge transfers in freezing water or melting ice, or between colliding ice particles at different temperatures. All these theories depend in one way or another on the differential diffusive mobility of ions of opposite sign in water and ice, the lattice defects in ice, the water–ice boundary and thermal gradients in ice. Facts concerning these theories, obtained mainly from laboratory studies, strongly suggest, however, that the sign of the charging depends mainly on small quantities of chemical additives or impurities in the water. The degree and kind of impurities varies from one locality and time to another, depending on the aerosol content of the air. The dependence of the sign of charging on particular local or temporal characteristics of the air detracts from acceptance of these theories for general thunderstorm-charging mechanisms.

Electrical exchanges resulting from physical processes in thunderstorm clouds should always occur reproducibly in all locations and with chemical combinations natural to the atmosphere. Exchanges associated with collisions and disruptions of cloud and precipitation particles in preexisting electric fields are examples of such general processes.

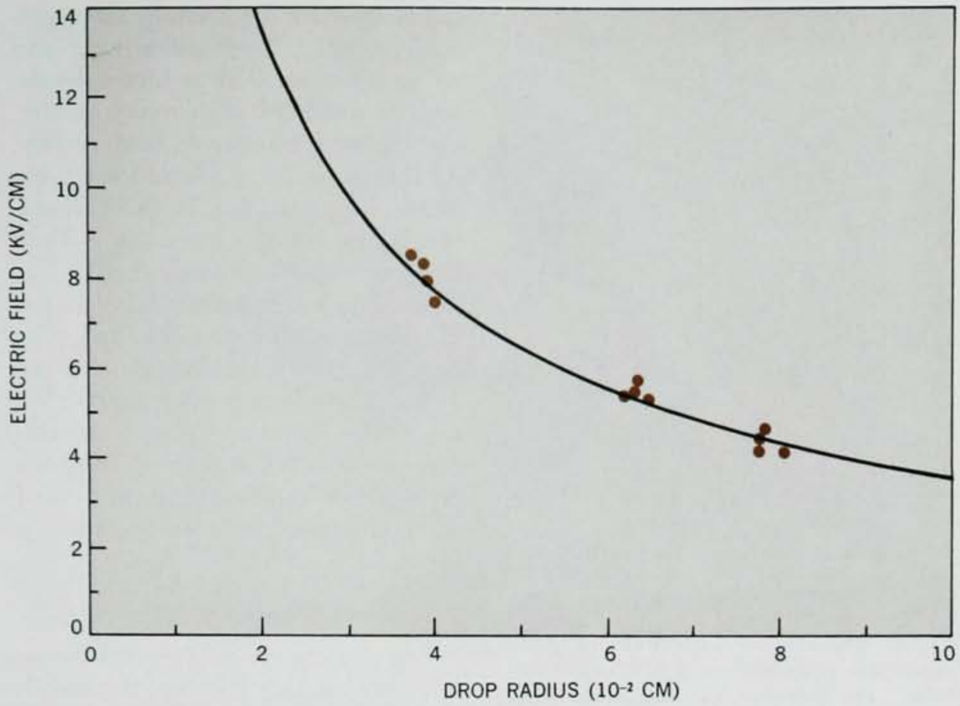
Electric fields in clouds

Thunderstorm clouds usually form in the lower layers of the atmosphere, where conductivity decreases exponentially with height and aerosols are



FREE-FALL TRAJECTORY of small drop relative to a larger one. **This computation** also depicts charge transfer (colored symbols) **on collision or near collision in the** electric field, for drops initially charged or uncharged. —FIG. 1

charged with an excess of positive ions. These charges produce electric fields that are directed downward throughout the troposphere, except when a cloud is present. The electric field of the atmosphere causes the capture of atmospheric ions of opposite sign by cloud droplets near the upper and lower boundaries of a cloud. The field inside the cloud is thus enhanced by the inverse ratio of the conductivities inside and outside. According to Paul A. Allee and Byron B. Phillips[6] the conductivities observed inside a large cloud chamber are 1/3 to 1/20 of those in cloud-free air; the field inside clouds could therefore be 3 to 20 times the normal "fair-weather" value of approximately 1 volt/cm.



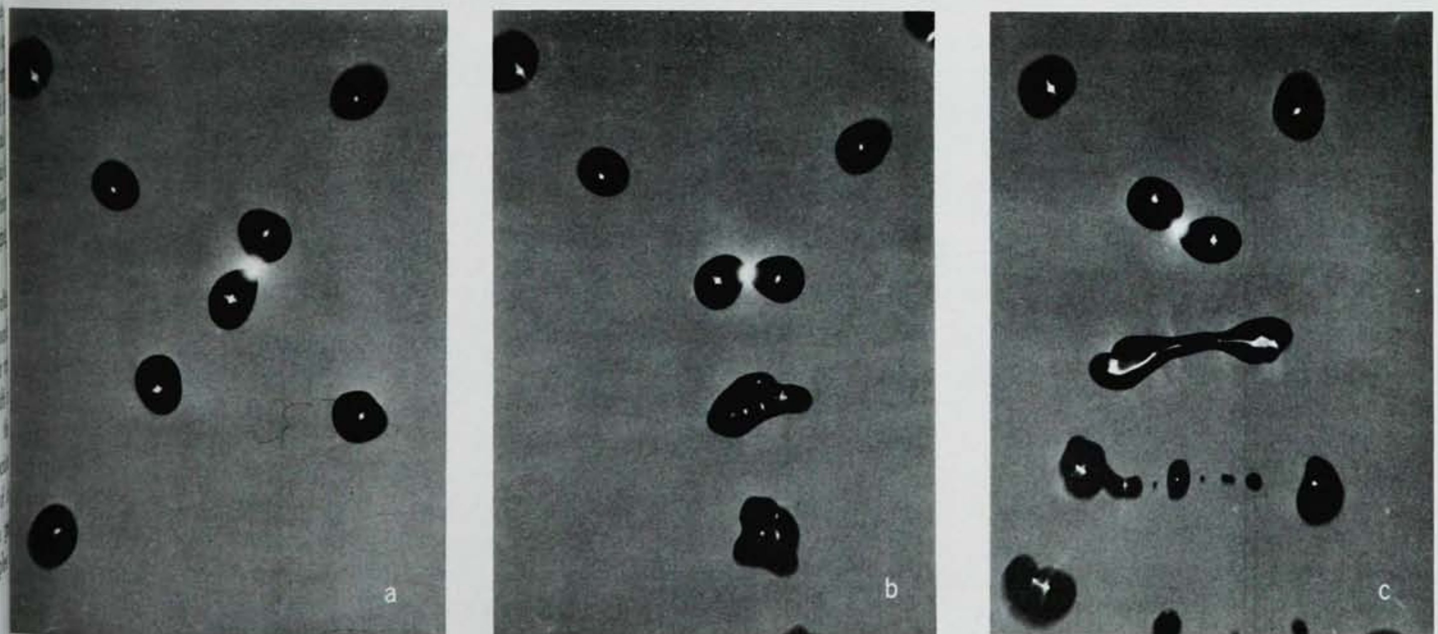
MINIMAL ELECTRIC FIELD required to produce a spark discharge between two uncharged equal-radius drops plotted against drop radius. The curve was computed with the assumption that the sparking potential for drops is the same as that for insulated spheres of the same radius and separation as the drops. —FIG. 2

Inductive charging

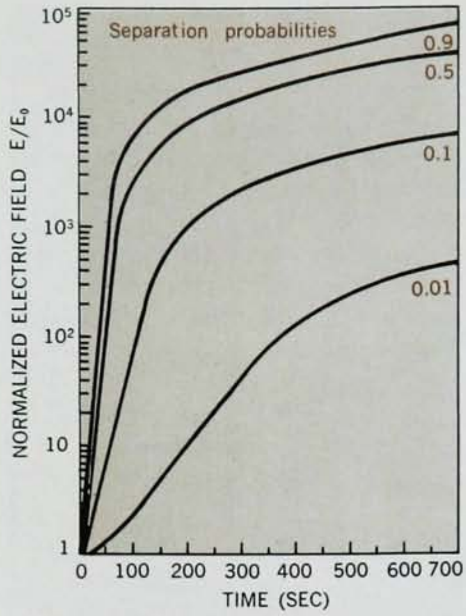
We can expect the relative trajectories of small cloud droplets, larger raindrops and frozen hydrometeors of roughly spheroidal shapes to be asymmetrical, as illustrated in figure 1. If a small drop, traversing this trajectory in a vertically oriented electric field, encounters a larger drop by electrical contact or by an electrical discharge and physically separates from it, each drop will become inductively charged. The drops may have been initially charged or uncharged. If they were charged initially, the original charges will add algebraically, with the inductive charges superimposed.

Because the larger particle falls faster, the charges, newly acquired by induction, separate and therefore enhance the existing field against the electrostatic forces trying to drive them together. In the atmosphere the energy for this charge separation and subsequent field enhancement comes, of course, from the gravitational potentials of cloud particles that have different sizes and different densities.

There are many other possibilities for the physical and electrical behavior of two drops and their frozen counterparts. However, the accretion and coalescence of charged particles does not appear as a net contribution to the charging process, because there are equal probabilities of charge accumu-



SPARKING between colliding drops. These drops are oppositely charged, and their radius is 3.67×10^{-2} cm. The bright spot between the central pair is integrated light from 25 000 discharges between drops. These examples show (a, left) a near-miss trajectory, (b, center) a direct-collision trajectory with coalescence and (c, right) a grazing-collision trajectory. —FIG. 3



ELECTRIC-FIELD GROWTH for four separation probabilities, 0.9, 0.5, 0.1 and 0.01. The calculations were made with observed thunderstorm particle distributions. Conductivity of air was taken to be 10^{-4} esu. —FIG. 4

lation and charge destruction for opposing encounters of equal probability. Thus the fraction of the particles accreting and coalescing is not counted upon to increase the field. The net charging processes appear to be universal in that they depend only on basic charge transfer and physical interaction mechanisms acting everywhere without special or localized chemical, physical and temperature conditions. However, near or just below the level of the 0°C isotherm, the particles are large wet snowflakes, melting ice crystals, snow pellets, or hail. They are warmer and wetter than particles at higher levels; their conductivity is therefore greater, and charge is transferred more readily. As they are solid inside and relatively large, the probability of their separation after collision is high. Their large size and increasing density (as they melt) increase their fall velocity, relative to smaller particles, and offer greater capacity for acquiring charge by induction from a small initial electric field. Rapid and strong electrification near or below the 0°C level can therefore be anticipated, regardless of other charging processes at work in the cloud.

Discharges between drops

When the charge difference between approaching drops is sufficiently great, sparks appear between the drops. Such sparks have been observed to occur with drops as small as 8×10^{-3}-cm radius. Alan Miller, Claire Shelden and William Atkinson[7] demonstrated by spectrographic analysis that the spark forms in the air between the drops.

The colored points in figure 2 show some observations of the relationship between the ambient electric field and the radius of uncharged equal-radius drops required to initiate sparking between their near surfaces. The curve is the theoretically predicted ambient electric field that would cause electrical breakdown between two uncharged insulated conducting spheres of the same radii and separation as the drops at observed breakdown. Charles E. Abbott and I reported[8] these observations and their theoretical predictability in 1968. Similar observations were made on discharge thresholds between oppositely charged drops by Atkinson and me.[9]

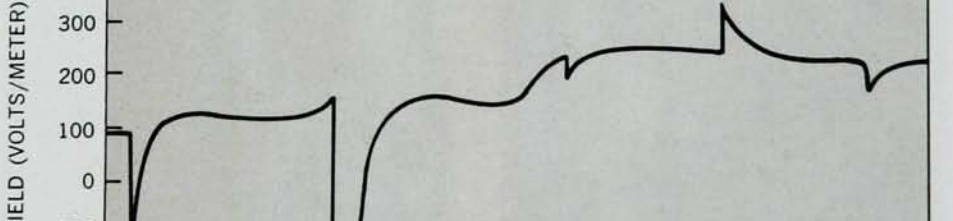
Atkinson and Ilga Paluch,[10] and Joe Keeney,[11] have studied the electromagnetic emission at microwave frequencies that arises from the sparks. Using observations of charges and drop sizes, Atkinson and I estimated that the microwave radiation from terrestrial thunderstorms, resulting from the vast number of randomly spaced discharges that could be expected to occur between colliding drops, could be as much as 117 K.

These microdischarges and similar charge transfers below the sparking mode between cloud particles in clouds depend on conditions present in all thunderstorms. If sufficiently frequent, they could significantly affect the separation of charge and the growth of high electrostatic fields in thunderstorms.

Colliding drops

Figures 3a, b and c show the spark discharges between pairs of charged drops and illustrate three separate consequences of the interaction between the drops. In figure 3a, pairs of drops make a grazing collision or close passage near the center of the photograph. Figure 3b illustrates a similar situation, but here the drops collide more nearly head-on. After sparking they coalesce, forming a new drop with the volume of the original pair. In figure 3c, the collision path is less direct than in figure 3b but more direct than in figure 3a. Here the drops coalesce after sparking, but because of their previous relative inertia the new drop then separates into a number of smaller ones.

The electrical consequences of these three events are quite different. In the situation of figure 3a some or all of the charge difference may be neutralized. In figures 3b and 3c the charges on the two drops combine. In the presence of an ambient vertical electric field, events like those depicted in figure 3a leave the drops charged in a manner similar to the process illustrated schematically in figure 1. The duration of the spark discharge is about 10^{-9} sec or less, but the charge transfer below the sparking mode is limited by the bulk relaxation time of water (10^{-4} to 10^{-5}



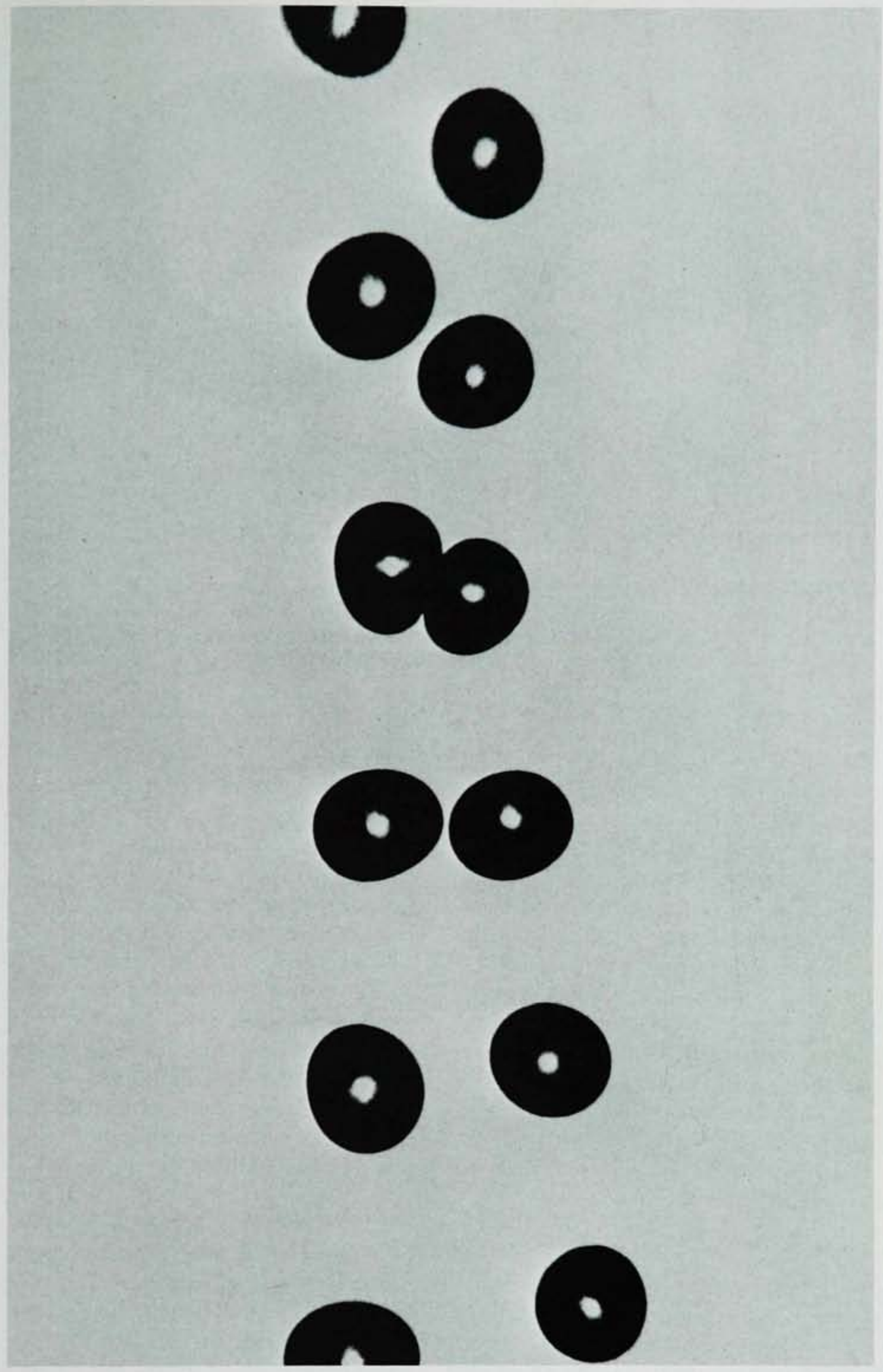
THUNDERSTORM. These variations in electric field at Boulder, Colo. on 15 Sept. 1966 resulted from a distant thunderstorm. Compare the field variations between lightning flashes with the theoretical curves of figure 4. —FIG. 5

sec). The drops shown in figure 3c, if they are in an electric field, transfer charge three times before they separate completely. Just before they touch, or as they are touching, charge is transferred inductively according to the direction of the ambient field. Upon coalescing this charge is quenched. When the newly formed drop breaks up, charge is transferred again under the influence of the ambient field. If oriented downward, this field inductively charges the portions of the drop that separate from the top with a negative charge and those separating from the bottom with a positive charge. Normally in clouds the collision between drops results in the relatively smaller particles receiving the positive charge and the relatively larger particles receiving a net negative charge.

Quantity of charge transferred

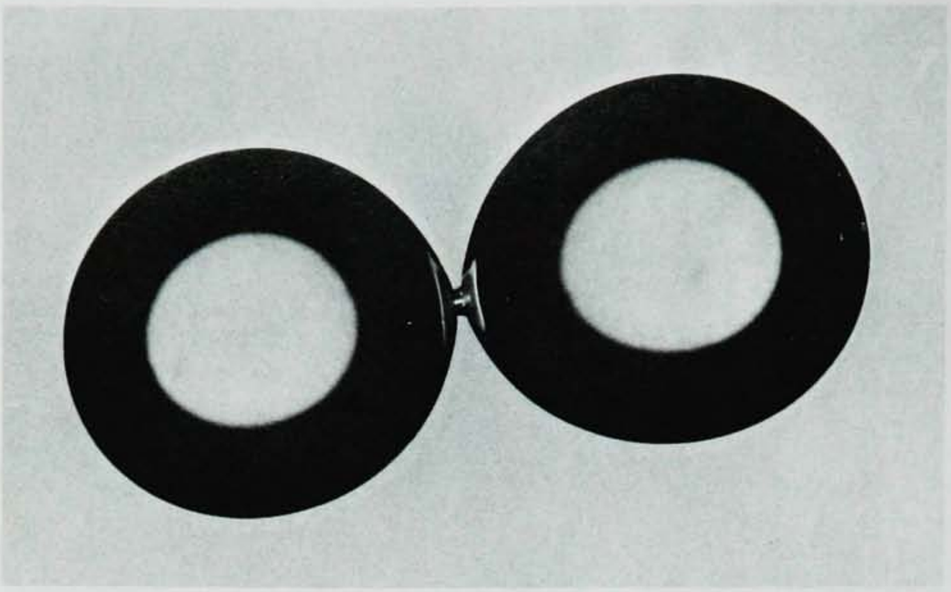
Using the techniques developed in studies of the spark discharges, Abbott and I have measured[8] the charge transfer between uncharged drops in electric fields above and below the sparking threshold, and we compared the laboratory results with computations from the theoretical work by Milford H. Davis.[12] We found theory and observation to agree remarkably well.

By considering the charge transfer between bouncing or disrupting collisions in an electric field, I have computed[13] the net effect on the time rate of growth of the gross electric field resulting from collisions between both frozen and liquid particles. I used known particle distributions observed within active thunderstorms. The particle distribution is considered fixed with respect to time, and the growth of the electric field starts when the cloud contains the drop distribution employed, which happens when the storm has reached a precipitation phase and is a mature cloud. The ratio of the electric field at that time to the field some time later is shown in figure 4. The curves correspond to different probabilities of separation following collision in the field, and they are intended to represent extremes from an all-water cloud (separation probability 0.01) to an all-ice-particle cloud (separation probability 0.9) with separation probabilities of 0.1 and 0.5 in between. The shape of these curves compares favorably with the shape of observed field-growth curves shown in figure 5. The time required for field build-up or recovery after a lightning flash compares favorably with observations, even when the initial field is not greater than that of fair weather, 1 volt/cm. Because of changes in the distance of the observation point from the thunderstorm discharges, the observed field excursions are sometimes inverted, as seen in parts of figure 5.



BOUNCING DROPS. These drops, of 4 $\times$ 10^{-2}-cm radius, bounce without coalescing after their collision. No charge is transferred, which is evidence that they do not touch; a thin layer of air remains between their near surfaces. —FIG. 6

The most favorable conditions for rapid electrification according to this mechanism are an initial electric field of 1 volt/cm or greater directed downward and numerous large, mostly solid, particles at or near 0°C. These conditions very closely parallel those associated with the maximal charging conditions in clouds that develop into thunderstorms. There now appears to be a high probability that the electrifi-



STRONG-FIELD COALESCENCE. Here two uncharged drops, of 7.8×10^{-2}-cm radius, collide in a uniform field of 3.85 kV/cm parallel to their line of centers. The photograph was taken 15 microsec after the start of charge transfer, when charge has stopped flowing but water continues to flow into the neck. —FIG. 7

cation process in clouds is strongly interrelated with the precipitation growth process involving coalescence and accretion. Many important details of these processes are unknown. Some of the results of studies made in the NCAR laboratories promise interesting information for specific cases. For example when the drops do not coalesce their near surfaces are flattened, with a thin layer of air remaining between them. The deformation of the near surfaces of bouncing noncoalescing drops is shown in figure 6.

Bouncing drops

No charge is transferred when drops bounce in an electric field in the manner of figure 6. This observation is evidence that, even though they deform considerably, their near surfaces do not touch during the bouncing process. When the drops used in this experiment collide in fields greater than 25 volts/cm they coalesce, and the flow of liquid between them is accompanied by a flow of charge. Figure 7 shows the situation 15 microsec after coalescence has started. By this time the charge transfer between drops has stopped, but the water continues to flow into the neck between the drops where the new drop will form. The charge-flow period agrees well with the computed relaxation time.

The picture changes, in a way important for cloud-physics interpretation, when electric fields and charges are weak. Figure 8 illustrates coalescence of two 3.9×10^{-2}-cm drops with an immeasurably small field and charge. In part a of the figure the two drops are deformed by impact. In part b coalescence has started with the formation of the new drop surface in the central volume, within which small air bubbles, some hundredths of millimeters in radius, have been entrapped. R. W. Park and E. J. Crosby[14] also report observing the trapping of bubbles during the coalescence of unelectrified drops.

Bubble trapping

The trapping of bubbles is important in understanding hail growth; small air bubbles cause hail to be opaque. With high fields or charges, the near surfaces of freezing drops would reach out for each other as in figure 7, precluding any possibility of air being trapped. Hailstones with concentric clear and opaque layers may thus reflect differences in electrical environment during their growth periods.

In figure 8c the new central-volume drop surface is growing; in part d the relative momentum of the fluid in the original drops has forced the new drops into a configuration of excessive curvature and high internal pressure. This high internal pressure, directed away from these regions of strong curvature and assisted by the inertial reaction of the flow in opposite directions, causes a horizontal elongation that reaches another extreme in part f. From this condition on, the new drop enters a damped-oscillation phase between configurations resembling figures 8d and 8f until a new spheroidal shape is assumed.

Satellite drops

Figures 9a, b and c illustrate the behavior of two dissimilar-sized drops in free fall. Part a shows a drop pair just prior to collision; part b shows a pair immediately after collision; part c shows the ejection of a small satellite drop formed after the collision and coalescence. The satellite drop is much smaller than either of the original drops—less than 7.5×10^{-3}-cm radius. Satellite drops may form new centers for droplet collection and therefore aid the precipitation-growth process by a chain reaction, as envisioned by Irving Langmuir.[15] In an electric field there would be charge separation in which charge of one sign appears on the large drop and charge of the opposite sign on the satellite. This charge separation normally acts to increase the existing field when the satellite is ejected from the base of the larger drop.

It is important for understanding the physics of clouds to attempt to fit general theories to the different classes of events I have described. Although the electrostatic principles discussed in the study of the induction-charging process in clouds are universal, considerable extrapolation is necessary to apply the results to coalescence or electrification of drops of different liquids and in different size ranges in natural clouds. More information is needed on mechanical and hydrodynamic consequences of collisions between charged and uncharged drops, over a wide range of drop sizes, in the presence and absence of electric fields. Our ability to predict the amount of charge transferred between colliding drops in an electric field may, however, be of immediate significance to understanding the distribution of electricity in thunderstorms.

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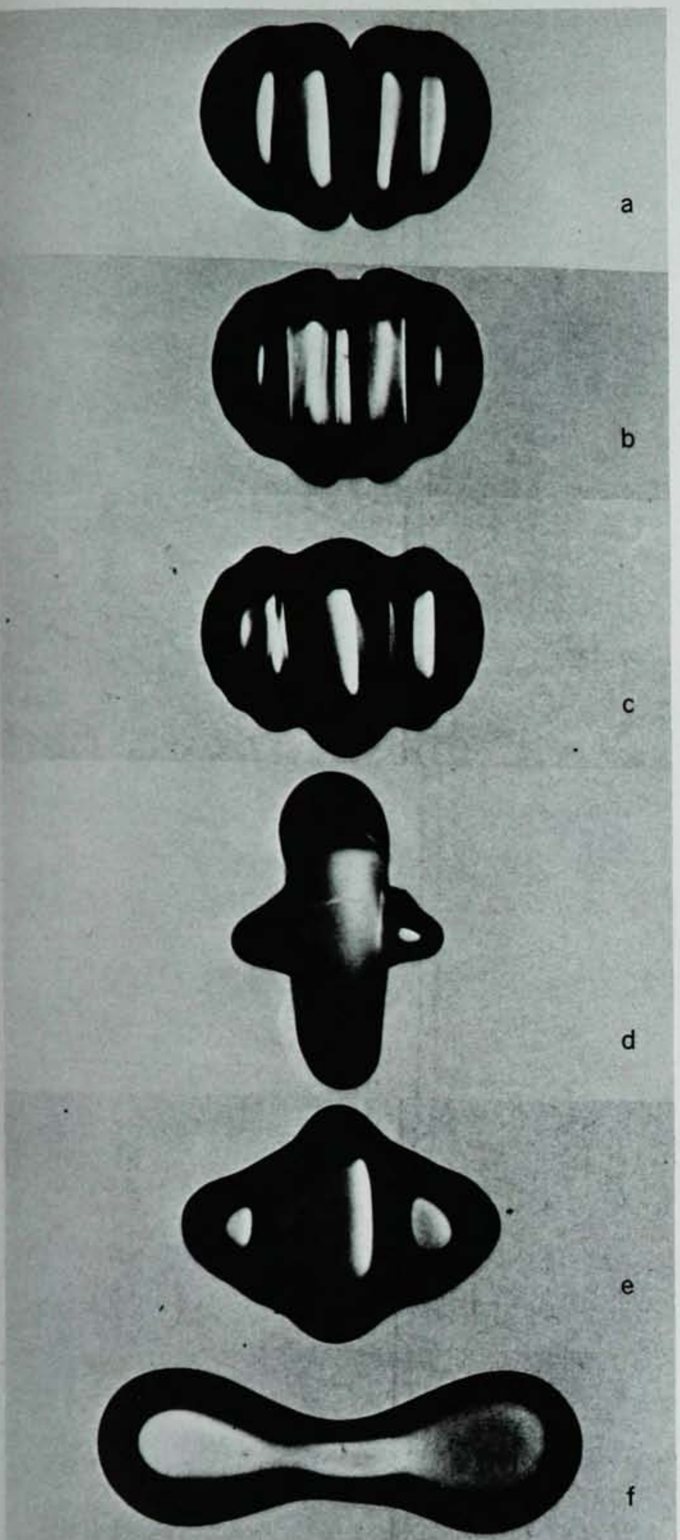
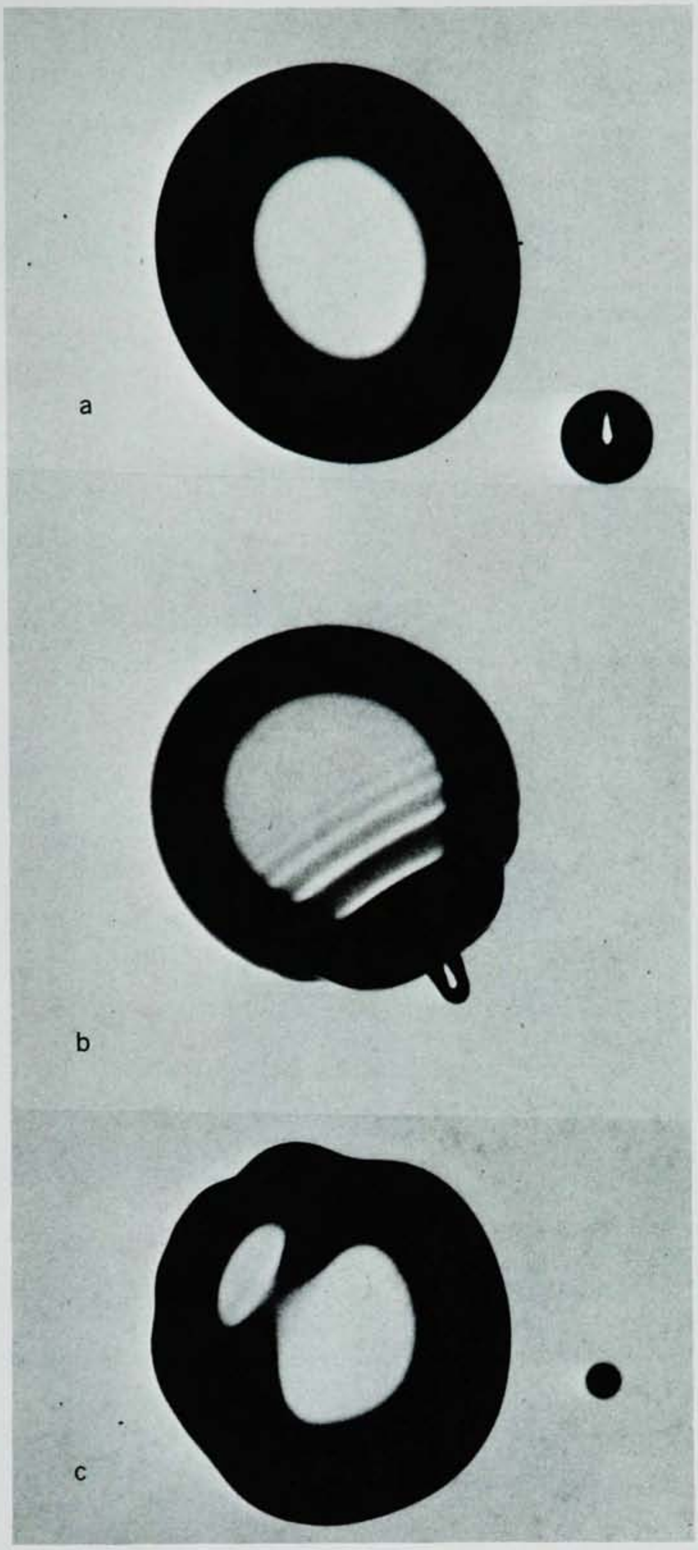


WEAK-FIELD COALESCENCE, shown in successive stages at intervals of 50–100 microsec for drops of 3.9×10^{-2}-cm radius. The electric field is too small to measure. —FIG. 8



FORMATION OF SATELLITE DROP after collision and coalescence involving a 1.96×10^{-2}-cm drop and an 8.06×10^{-2}-cm radius drop in free fall. —FIG. 9

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