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The Electrification of Thunderstorms

Although it has been known for two centuries that lightning is a form of electricity, the exact microphysical processes responsible for the charging of storm clouds remain in dispute

by Earle R. Williams

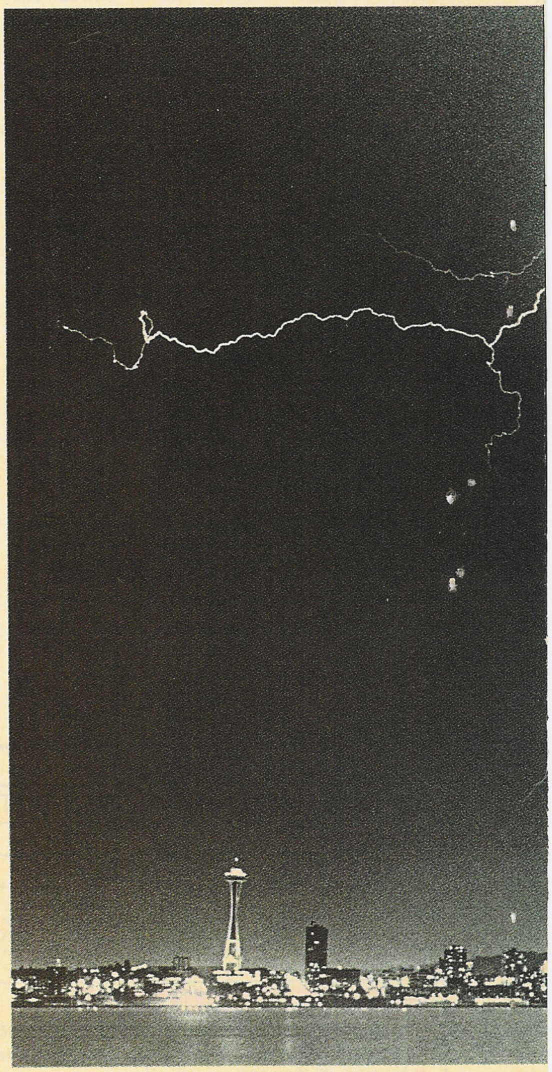
Lightning is one of the commonest and most spectacular of natural phenomena, and in the two centuries since Benjamin Franklin demonstrated that a lightning bolt is a giant electrical discharge, lightning and thunderstorms have been the subject of numerous scientific investigations. Yet, in spite of a barrage of new equipment and investigative techniques, lightning's exact origins and the mechanism by which rain clouds are electrified remain elusive.

The intractability of the problem stems from the fact that the physics of lightning and thunderstorms spans 15 orders of magnitude in scale. At the one end are the atomic phenomena that initiate the electrification of the storm cloud and that take place on scales of 10^{-13} kilometer; at the other end is the air motion of the full thundercloud, which completes the charging process and may take place over scales of tens or hundreds of kilometers. At each scale significant physics is not understood.

Franklin himself, perhaps unknowingly, identified one of the basic difficulties. In 1752 he observed that "the clouds of a thunder-gust are most commonly in a negative state of electricity, but sometimes in a positive state." Whether this ambiguity is the result of faulty observations or inherent in nature has been clarified only recently. Nevertheless, since Franklin's words were written, it has been accepted that lightning is the transfer of either positive or negative electric charge from one region of a cloud to another or between the cloud and the earth. For this charge transfer to take place the cloud must be electrified, that is, the positive and negative charges must be separated. How does charge separation come about?

As will become apparent, only a partial answer to this question can be given. In objects one ordinarily encounters, such as coffee cups or telephones, there are equal numbers of positive and negative charges; moreover, these charges are spread uniformly over the object, which is then said to be electrically neutral, or uncharged. Many microphysical processes, however, might cause the charges to separate, with the result that, although the object as a whole remains neutral, one region has more positive or negative charges than another. The object is then said to be charged or electrified. Charge separation is measured in volts; the greater the separation, the greater the voltage. When you walk across a room, the entire room remains neutral but the action of your shoes on the rug may charge the rug with one polarity and your shoes and body with the opposite polarity. This can lead to a potential difference of 100,000 volts over a distance of centimeters, a charge that is

EARLE R. WILLIAMS is assistant professor of meteorology in the Department of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology. He received a B.A. in physics at Swarthmore College in 1974 and a Ph.D. in geophysics from M.I.T. in 1981. His interest in lightning stems from a summer at the Brookhaven National Laboratory, where he observed large-scale electrical breakdowns on high-voltage terminals, a great nuisance to nuclear physicists but sufficiently spectacular to initiate a career in the physics of thunderstorms. His current research interests center on radar meteorology.



LIGHTNING STRIKES SEATTLE in an unusually large storm on July 31, 1984. A typical lightning bolt bridges a potential difference of several hundred million volts; it transfers the charge of approximately 10^{20} electrons in a fraction of a second, for a peak current of up to 10 kiloamperes. A moderate thunderstorm generates several hundred megawatts of electrical power, equivalent to the output of a small nuclear power plant.

evident when you grasp the doorknob.

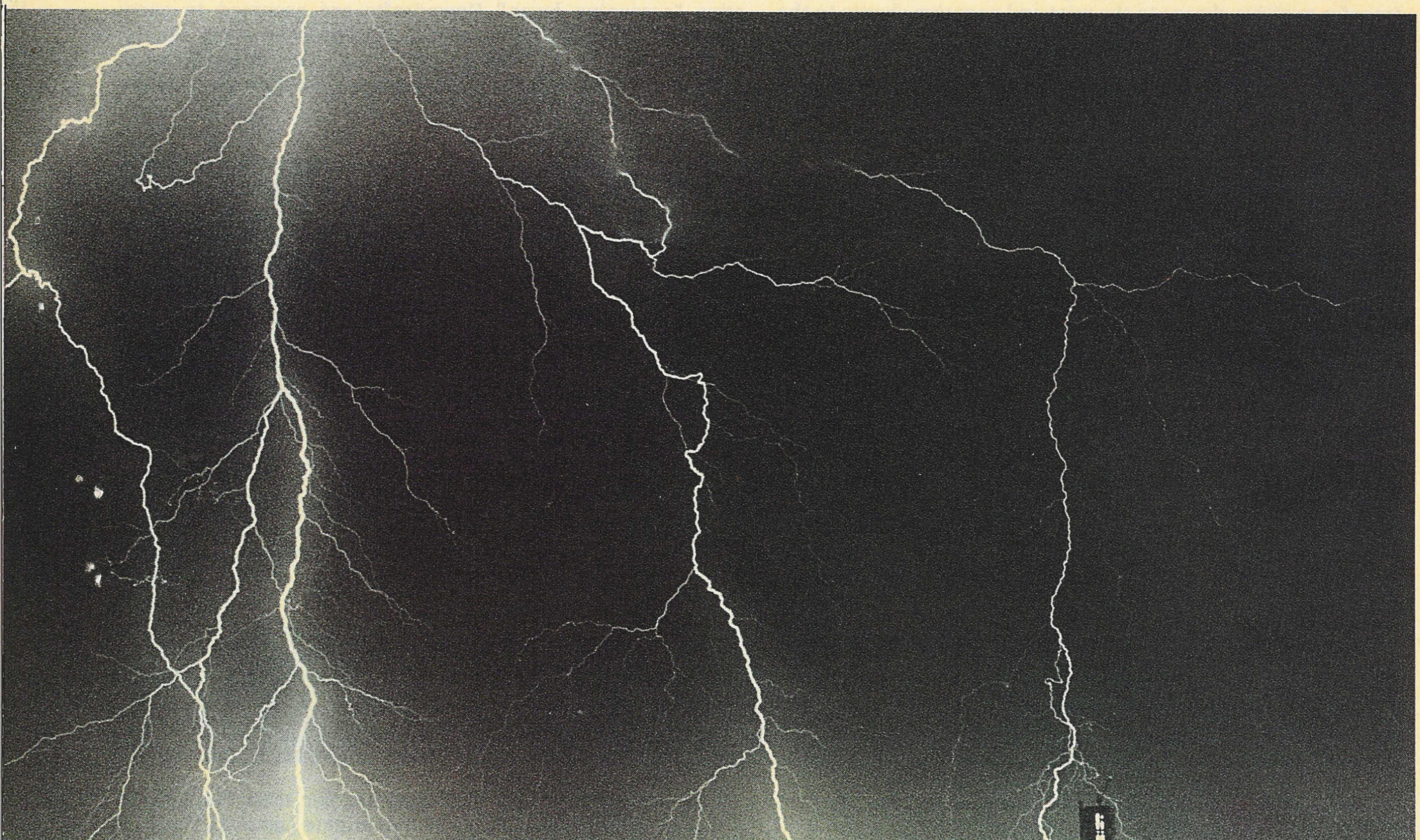
A typical lightning bolt represents a potential difference of several hundred million volts, and it may transfer 10 or more coulombs of charge to the ground; this is the charge carried by about 10^{20} electrons. The transfer of one coulomb of charge in one second is by definition an electrical current of one ampere. A lightning bolt therefore represents a current of much more than 10 amperes since its duration is much less than one second. Storm clouds of modest size produce a few flashes per minute and a power of a few hundred megawatts—that of a small nuclear power plant. To find the correct charge distribution and the physical mechanism behind such voltages and power outputs is the main task of thunderstorm physics. Historically investigations have centered on the electrical structure of clouds.

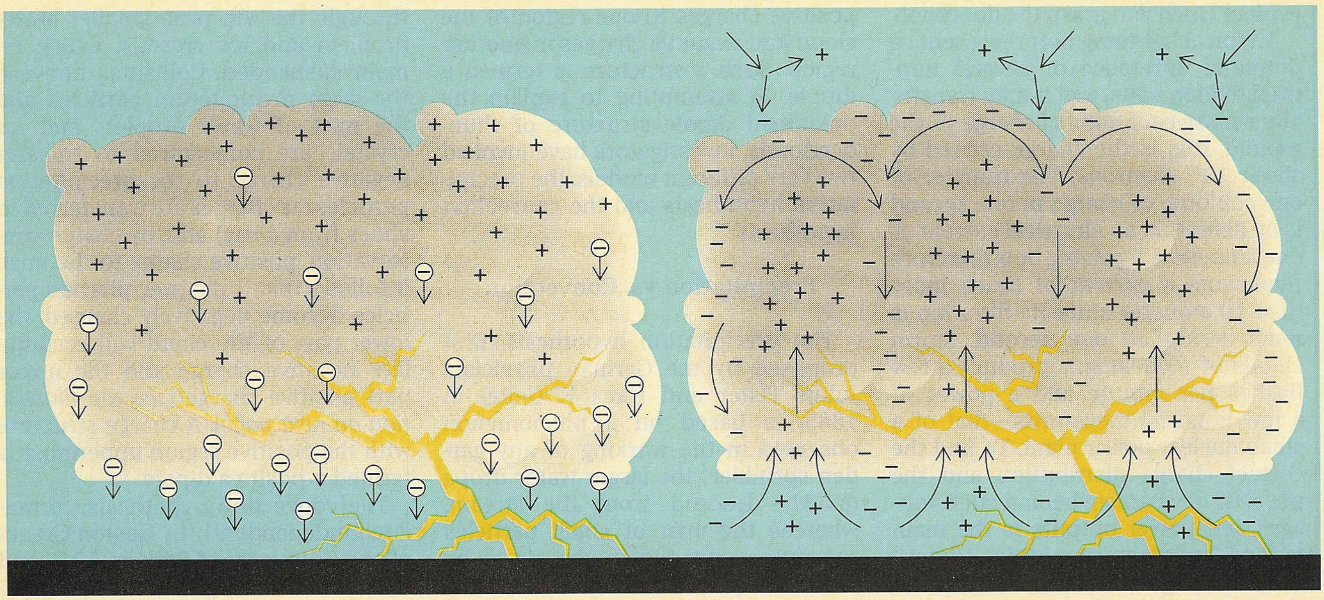
After Franklin's observation it was natural to assume that the charge distribution in a rain cloud conformed to the simplest pattern imaginable: positive charges in one region of the cloud and negative charges in another region. Such a structure is termed a dipole. In attempting to explain the presumed dipole structure of thunderclouds, investigators have invoked two very different models: the precipitation hypothesis and the convection hypothesis.

Precipitation vs. Convection

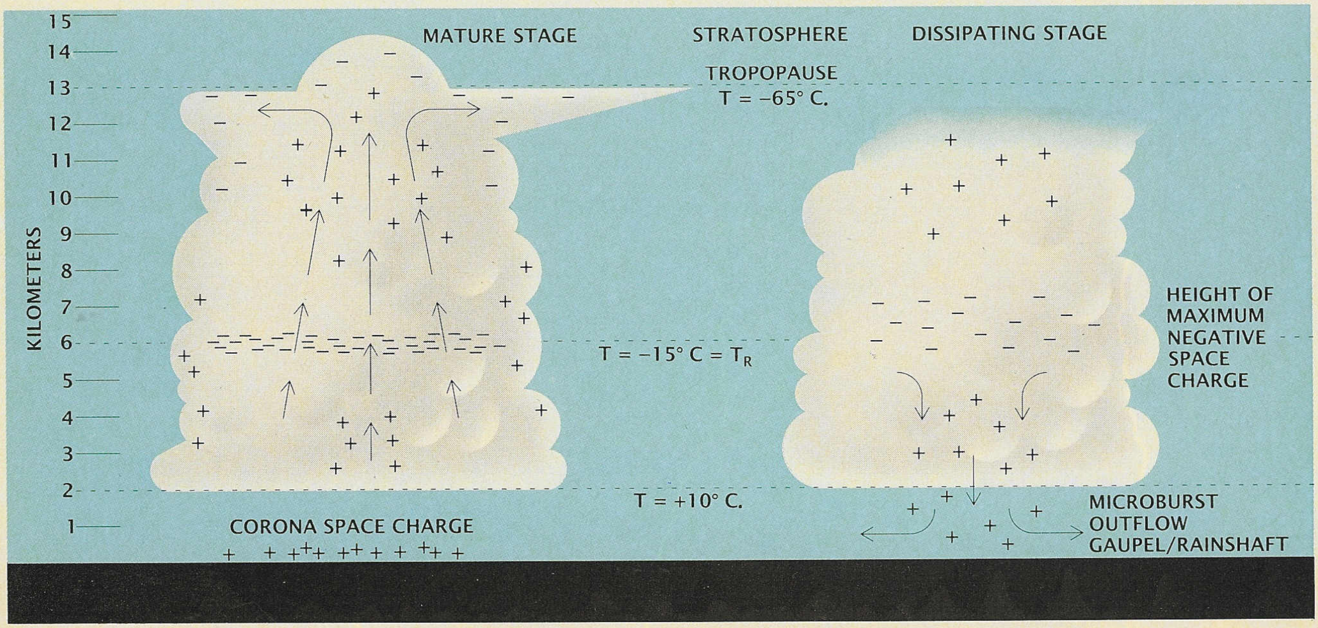
The precipitation hypothesis, first proposed by the German physicists Julius Elster and Hans F. Geitel in 1885, is based on a phenomenon observed in the working of any garden sprinkler: the larger water drops quickly descend from the stream, whereas the mist of small particles remains suspended in the air to be blown away by the wind. In the same way, the precipitation hypothesis assumes that raindrops, hailstones and graupel particles (millimeter-to-centimeter-size ice pellets) in a thundercloud are pulled by gravity downward through the air past smaller water droplets and ice crystals, which remain suspended. Collisions between the large precipitation particles and the mist of water droplets and ice crystals are conjectured to transfer negative charge to the precipitation particles (as charges are transferred to shoes from a rug) and, by charge conservation, positive charge to the mist. It follows that if the precipitation particles become negatively charged, the lower part of the cloud will accumulate negative charge and the upper part positive charge [*see top illustration on next page*]. A charge structure with the positive region uppermost is termed a positive dipole.

The convection hypothesis, formulated independently by Gaston Grenet of the University of Paris in 1947 and by Bernard Vonnegut of the State University of New York at Albany in 1953, is somewhat more complicated. The analogue here is the familiar Van de Graaff generator. In such a device a positive or negative electric charge is





TWO MODELS attempt to explain the electrical structure of thunderclouds. The precipitation model (*left*) suggests that gravity pulls heavy raindrops, hailstones and millimeter-size ice particles called graupel past smaller water droplets and ice crystals, which remain suspended. Collisions between the falling particles and the suspended mist are conjectured to transfer positive charge to the mist and negative charge to the heavier particles. As these heavier particles fall, the lower part of the cloud becomes negatively charged and the upper part becomes positively charged—a structure known as a positive dipole. The convection hypothesis (*right*) proposes that warm air currents carry positive charges released from the earth's surface to the top of the cloud. Negative charges, produced by cosmic rays above the cloud, are attracted to the cloud's surface by the positive charges within it. The negative charges attach themselves to cloud particles to form a negative "screening layer." Downdrafts are assumed to carry the negative charges downward; this process again results in a positive dipole. Note that the convection model invokes no precipitation and the precipitation model no convection.



ACTUAL STRUCTURE of a thundercloud is not dipolar but tripolar, with a main negatively charged region sandwiched between two positively charged regions. In a mature thundercloud (*left*) the main region of negative charge is at a height of about six kilometers and a temperature of about −15 degrees Celsius. Its thickness is only a few hundred meters, giving it a pancake shape. The upper positive region often extends to the tropopause, at a height of about 13 kilometers. At the very top of the cloud there is a thin layer of negative charges called the screening layer; its origins may be due to cosmic rays, which ionize air molecules. At the bottom of the cloud there is a second region of positive charge, smaller than the first. In a mature thundercloud updrafts dominate (*arrows*), but in a dissipating thundercloud (*right*) the lower region of positive charge precipitates out with strong downdrafts. The naive precipitation model does not account for the tripolar structure of thunderclouds. The convection hypothesis does this by assuming that the lower positive region is produced by so-called corona discharge given off by sharp objects on the earth. Recent evidence, however, indicates that the correct explanation for the tripolar structure lies in the microphysics of charge transfer between graupel particles and ice crystals.

sprayed onto a moving rubber belt, which then transports the charges, or ions, to a high-voltage terminal. The convection model assumes that the electric charges in the cloud are supplied initially by two external sources. The first source is cosmic rays, which impinge on air molecules above the cloud and ionize them (separate the positive and negative charges). The second source is the strong electric field around sharp objects at the earth's surface, which produces a "corona discharge" of positive ions. These positive ions are carried upward by warm air, which, rising by convection, acts like the belt on the Van de Graaff generator. After reaching the upper regions of the cloud, these positive ions attract the negative ions that were formed by cosmic rays above the cloud. The negative ions enter the cloud and quickly attach themselves to water droplets and ice crystals, thereby forming a negatively charged "screening layer." By hypothesis the downdrafts at the cloud's periphery then carry the negatively charged particles of the screening layer downward; this again results in a positive dipole structure.

Although precipitation and convection are observed in all clouds that produce lightning (and these phenomena are indeed inseparable in large clouds), one sees that the elementary precipitation hypothesis invokes no convection and the convection hypothesis invokes no precipitation. The marked distinction between the two models has played an important role in guiding investigators toward an understanding of the respective roles of precipitation and convection in the electrification of clouds.

These models were developed to explain the dipole structure of thunderclouds. But, as already mentioned, Franklin's first observation in 1752 hints at an ambiguity: Is the positive or negative charge uppermost? This question led to an early controversy between C. T. R. Wilson and George C. Simpson over the charge structure of thunderclouds. The debate is instructive, for it shows some of the difficulties in collecting meaningful thunderstorm data.

Positive Dipole or Negative?

In the 1920's Wilson, who earlier had invented the cloud chamber, made observations of a number of thunderstorms from a distance and concluded that the basic structure of a thundercloud was that of a positive dipole. At about the same time Simpson, measuring the charge on rain falling from thunderclouds, concluded the opposite: that the lower region of a thundercloud was positively charged and the upper region was negatively charged—a negative dipole.

It is only within the past 20 years that investigators have been able to explain these seemingly incompatible results. With the benefit of hindsight one can say the most important reason for the persistence of the discrepancy is that one rarely measures the charge in a thundercloud; it is inferred from a measurement of the cloud's electric field. An electric field surrounding a charged body is analogous in almost every respect to the gravitational field surrounding a massive body. Both fields cause other objects within them to move; gravity attracts massive objects, whereas an electric field attracts or repels charged objects. The gravitational or electrical force acting on such "test particles" diminishes with the square of the distance between the test particle and the central body. Both fields are therefore characterized by a strength (determined by the distance to the attractive or repulsive body) and a direction (attractive or repulsive). Fields characterized by a strength and a direction are called vector fields.

When more than one charged body is present, the electric field can become very complicated. Moreover, any number of charge configurations can produce the same field strength and direction at a given point. As a result a single measurement of the electric field cannot uniquely determine the charge distribution. Many measurements are required; in principle one must actually measure the electric field everywhere to deduce the true charge distribution. Wilson and Simpson each made measurements from a single position, which is not enough to infer the charge structure correctly.

Since the Wilson-Simpson controversy, 50 more years of observation have established that the basic structure of thunderclouds is not dipolar but tripolar: there is a main region of negative charge in the center with one region of positive charge above it and a second, smaller region of positive charge below it [*see bottom illustration on opposite page*]. The most notable feature of the main, negatively-charged layer is its pancake shape: its vertical thickness is less than a kilometer, but it may extend horizontally several kilometers or more. It is at an altitude of approximately six kilometers, where the temperature is roughly −15 degrees Celsius. Under conditions prevailing there all three phases of water—ice, liquid and vapor—can coexist. The largest electric fields in the thundercloud are found at the upper and lower boundaries of the main negatively charged layer.

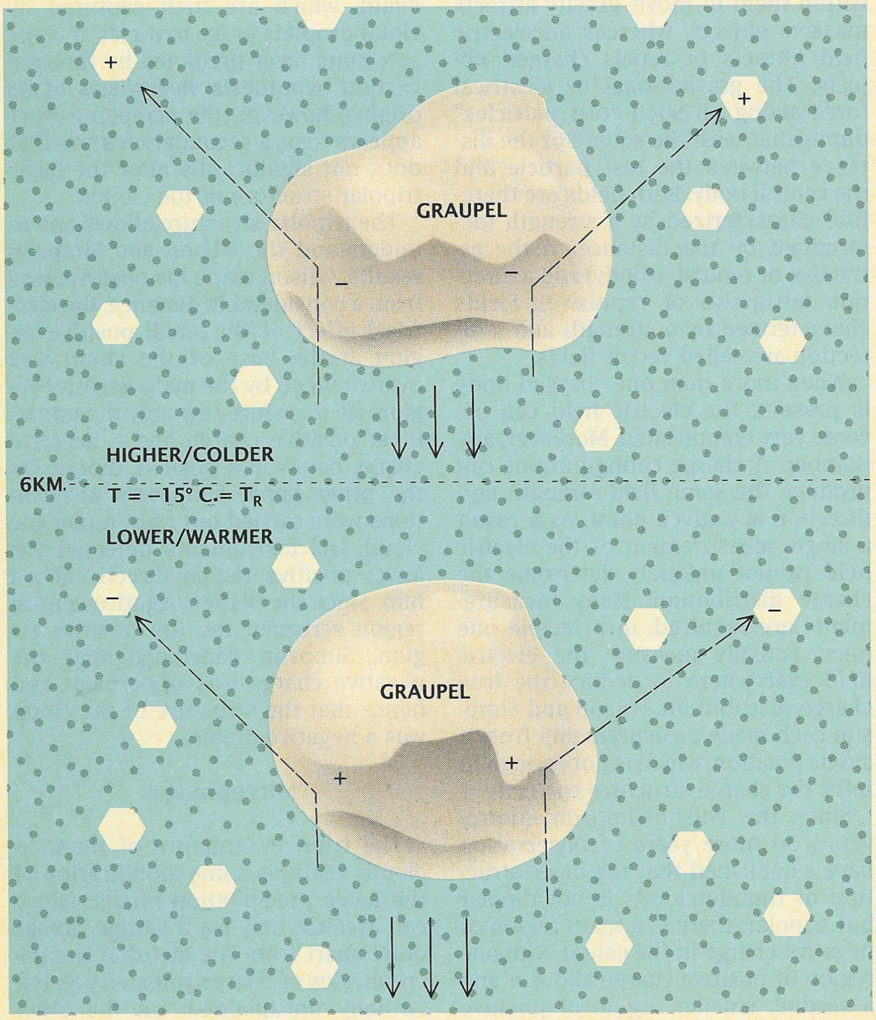
The upper region of positive charge is more diffuse than the negative layer and may extend vertically several kilometers—as high as the cloud itself. The lower region of positive charge, on the other hand, is so small that the electric field at the surface of the earth is frequently dominated by the main negative charge. One other feature is observed in many clouds: a layer of negative charge, about 100 meters thick, above the upper positive region. This layer may result from negative ions produced above and outside the cloud, which are then captured by cloud droplets or ice particles; it is the screening layer predicted by the convection hypothesis. Regardless of its origins, however, the screening layer appears to be a secondary feature that does not significantly alter the basic tripolar structure of the cloud.

The tripolar structure allows one to understand the Wilson and Simpson results. Wilson made his observations from a considerable distance; the electrical effect of the small positive region at the base of the cloud was overwhelmed by the main negative region. He therefore saw only the uppermost positive charge and a negative charge below it: a positive dipole. On the other hand, Simpson's observations were carried out right under the cloud. His instruments detected the lower positive region directly above him. Since the higher negative central region screened the top positive region, Simpson concluded that the negative charge was uppermost and hence that the structure of the cloud was a negative dipole.

Microphysics

The tripolar structure of thunderclouds requires some modification of the naive precipitation model, which can account only for a simple dipole, quite apart from the fact that the microphysics of charge transfer was left virtually unexplained. On the other hand, it might seem that the convection model leads more naturally to a tripole structure because it assumes that corona discharge from sharp objects on the surface of the earth produces a flux of positive charges toward the base of the cloud. It has been widely believed this flux might account for the lower, positively charged region of the tripole. Recent measurements of the size of the flux, however, suggest that it may be an order of magnitude too small to account for the observed rate of cloud charging. Partly for this reason the convection model has fallen into disfavor. One therefore attempts to modify the precipitation model.

Several modifications of the precipitation model have been proposed to account for the lower positive charge region, as well as for the fact that rain ordinarily carries a positive charge. Simpson made the first attempt at explaining these observations. Empirically it is known from studies of waterfalls that the larger droplets selectively acquire a positive charge on breakup. (The amateur can perform this experiment by taking a microammeter on board the *Maid of the Mist* at Niagara Falls.) Simpson proposed that precipitating water droplets in a thundercloud also fragmented near the base of the cloud and thus accounted for the lower positive region. Measurements made under the main negative charge region in thunderclouds, however, show that precipitation particles carry charges that are substantially greater than those produced in the waterfall fragmentation process; this raises serious questions about whether fragmentation can account for the tripole's lower positive region. Furthermore, it is now recognized that most of the positively charged particles that fall below the main negative charge region are not water droplets but ice.



MICROPHYSICS OF CHARGE TRANSFER involves collisions between graupel particles and ice crystals. The heavy graupel particles fall through a suspension of smaller ice crystals (*hexagons*) and supercooled water droplets (*dots*). Laboratory experiments show that when the temperature is below a critical value called the charge-reversal temperature, T_R, the falling graupel particles acquire a negative charge in collisions with the ice crystals. At temperatures above T_R they acquire a positive charge. T_R is thought to be about −15 degrees C., the temperature of the main negative region found in thunderclouds; thus graupel picks up a positive charge when it falls below this altitude to higher temperatures. There is now evidence that these positively charged graupel particles form the lower positive region of the thundercloud tripole.

Ice plays a role in the other proposals to explain the thundercloud's tripole structure. Laboratory studies in the 1940's showed that ice particles pick up a strong positive charge in the course of melting. This observation is still often invoked to explain the lower positive region of the cloud. Although melting may conceivably explain the existence of positively charged particles at altitudes below 4,000 meters, where ice begins to melt in mid-latitude thunderstorms, it cannot, however, explain their existence at higher altitudes where positively charged particles are also observed.

Melting of ice does not appear to account for the observed tripole structure, but there is now considerable evidence that collisions between ice crystals and graupel particles play a fundamental role. Over the past 20 years laboratory studies by many investigators, notably Stephen E. Reynolds, Marx Brook and their collaborators at the New Mexico Institute of Mining and Technology, Tsutomu Takahashi of the University of Hawaii at Manoa and Clive P. R. Saunders, John Latham and Anthony J. Illingworth at the Victoria University of Manchester, have shown that when graupel particles collide with ice crystals, the polarity of the charge transferred to the particles is strongly dependent on temperature. Below a critical temperature, called the charge-reversal temperature, negative charge is transferred; at higher temperatures (corresponding to lower altitudes in thunderclouds) positive charge is transferred [*see illustration at left*]. The exact value of the charge-reversal temperature is still a matter of dispute, but most laboratory investigators agree that its value is between −20 and −10 degrees C.

Thundercloud observations by a variety of methods show that the main negatively charged layer is at an altitude where the temperature is about −15 degrees. The charge-reversal hypothesis then explains why negative charges are found less frequently below this altitude: the graupel particles become positively charged as they fall past and collide with suspended ice crystals. These falling positive charges form the lower positive region of the tripole. Moreover, the amount of charge transfer per collision in the laboratory is of sufficient magnitude to account for the charge transferred by lightning in clouds of modest electrical activity. The establishment of a charge-reversal temperature consistent with both laboratory experiments and thundercloud observations must be considered the main advance in thunderstorm electricity in the past two decades.

At the same time, the exact microphysical processes that would explain the systematic transfer of charge of one polarity to the graupel particles, as well as the reversal temperature, remain almost entirely unknown. The underlying physical mechanism may well be related to whatever causes the shoes to charge when one walks on a rug or a glass rod to charge when it is rubbed with a piece of wool. Although these phenomena were known to the ancients, however, the basic microphysics behind them remains to this day a neglected and unsolved problem. The lack of a microphysical description of static electrification is the most serious gap in the understanding of thundercloud electricity.

Convection

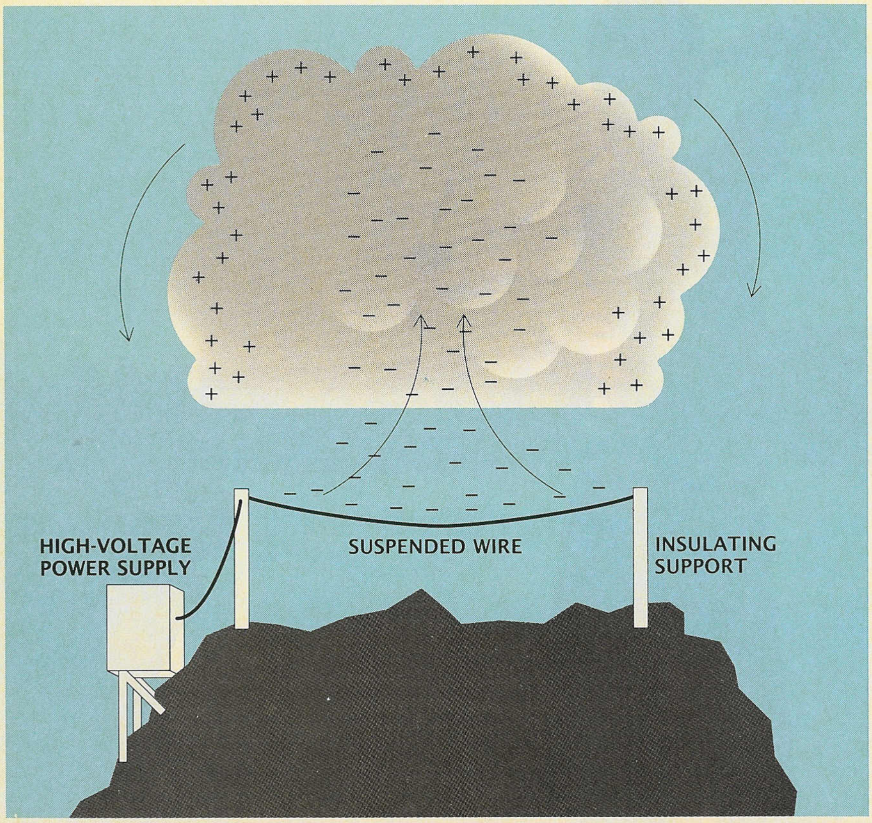
Although the convection model may be inadequate in accounting for the magnitude of the lower positive region, there is substantial evidence that thunderstorms are regions of vigorous updrafts and downdrafts; convection is indisputably present. It has also been observed that maximum lightning-flash rates are associated with the upward motion of graupel and hail above the main region of negative charge. This picture contradicts the naive precipitation hypothesis, in which only downward-moving graupel particles cause the electrification. It is probably the relative motion between the ice crystals and the graupel particles, however, that causes large-scale charge separation. The important requirement is that the ice crystals rise relative to the earth more rapidly than the graupel particles; this is equivalent to falling graupel. Moreover, vigorous updrafts are not only consistent with electrification but also essential for it: the updraft maintains the supply of supercooled water droplets above the charge-reversal altitude. These droplets provide for the growth of graupel particles required for electrification and, according to the laboratory experiments described above, negligible charge transfer takes place between graupel particles and ice crystals if the droplets are absent.

During the past decade thunderstorm downdrafts have been a growing concern from the point of view of aviation safety. Unusually strong downdrafts, termed microbursts by Tetsuya T. Fujita of the University of Chicago, are believed to have caused major commercial-airliner crashes. Recent studies of stationary thunderstorms have shown that these downdrafts follow by five to 10 minutes the time of peak updraft and maximum intracloud lightning activity; the downdrafts are also associated with the intense precipitation that results when the updraft collapses.

Measurements also show that the electric field at the ground reverses at this time from upward-directed to downward-directed. Positive charge is found on the precipitation, which suggests that the lower positive-charge region of the cloud is carried to the ground during the microburst phase of the downdraft. Both the intracloud lightning rate and reversals of the electric field might serve as valuable precursors to warn air traffic controllers about hazardous surface conditions.

Given that such strong convection currents are characteristic features of thunderstorms, one might think that the convection model holds promise in explaining some aspects of cloud electrification. As already mentioned, it does predict the screening layer. It is for these reasons that researchers, notably Charles B. Moore of the New Mexico Institute of Mining and Technology and Vonnegut, have continued to test the model. In their experiments air under a fair-weather cumulus cloud was charged by a wire connected to a high-voltage terminal [*see illustration at left*]. Electrical observations from an airplane showed that the charge released by corona discharge from the wire was carried up through the cloud by convective air motions. What is more, when positive charge was released, the top of the cloud became positively charged and the bottom negatively charged—a positive dipole. But when the polarity of the charges released from the power supply was changed to negative, the cloud took on a negative-dipole structure. These results indicated that convection was carrying charge to the top of the clouds.

The charge within the clouds produced by these experiments, how-



EXPERIMENTS by Charles B. Moore and Bernard Vonnegut test the convection hypothesis. Air under a cumulus cloud is charged positively by a wire connected to a high-voltage terminal. Measurements from an airplane show that the charges are carried upward through the cloud by convection. Reversing the polarity of the power supply reverses the cloud's polarity. The experiments indicate that convection is carrying the charges upward; the field produced, however, is about 1,000 times smaller than what is necessary to produce lightning in electrically active clouds, and so the relevance of these results to thunderclouds is still open to question.

INTRACLOUD lightning bolts are actually far more frequent than cloud-to-ground flashes but are seen less often because clouds strongly scatter light in the visible spectrum. Radar, radio-frequency direction finders and microphones, which "see" through clouds, are now helping investigators to study intracloud lightning.

LOOP-THE-LOOP shows that lightning paths do not follow obvious directions. Conflicting claims have appeared in the literature that the paths are random, are determined by the electric field configuration or are determined by the distribution of electric charge in space. The last explanation may account for many observations.

ever, was about 100 times less than is found in active thunderstorms and the electric field was more than 1,000 times less than that believed necessary to initiate lightning. Therefore the experiments did not directly test the role of convection in precipitating, electrically active thunderstorms and so the results cannot be said to strongly support the convection hypothesis.

Similar experiments have recently been performed under larger, precipitating clouds. Artificially released negative charge has resulted in a few cases with negative charge dominating above and positive charge below. This is consistent with the previous results and the convection hypothesis. The interpretation of the results is not unambiguous, however: because precipitation is now taking place, the lower positive charge may also be the result of the charge-transfer microphysics between ice and graupel already described.

Another observation relevant to the convection hypothesis is less ambivalent: the fact that the main negatively charged region is at a roughly constant altitude and temperature. In the convection model, air currents carry the negatively charged particles of the screening layer downward across distances of several kilometers. It is difficult to understand, then, why the negative charge should be mainly concentrated in a pancake-shaped region only a few hundred meters thick. As discussed above, this observation is better explained by charge-reversal microphysics and is perhaps the major argument against the convection model.

To sum up the status of the precipitation and convection models, the precipitation model can account for more aspects of cloud electrification than the convection model, but it does so by ignoring one of the most prominent features of thunderstorms: convection. Presumably in the future the best aspects of both models will be combined in one comprehensive theory.

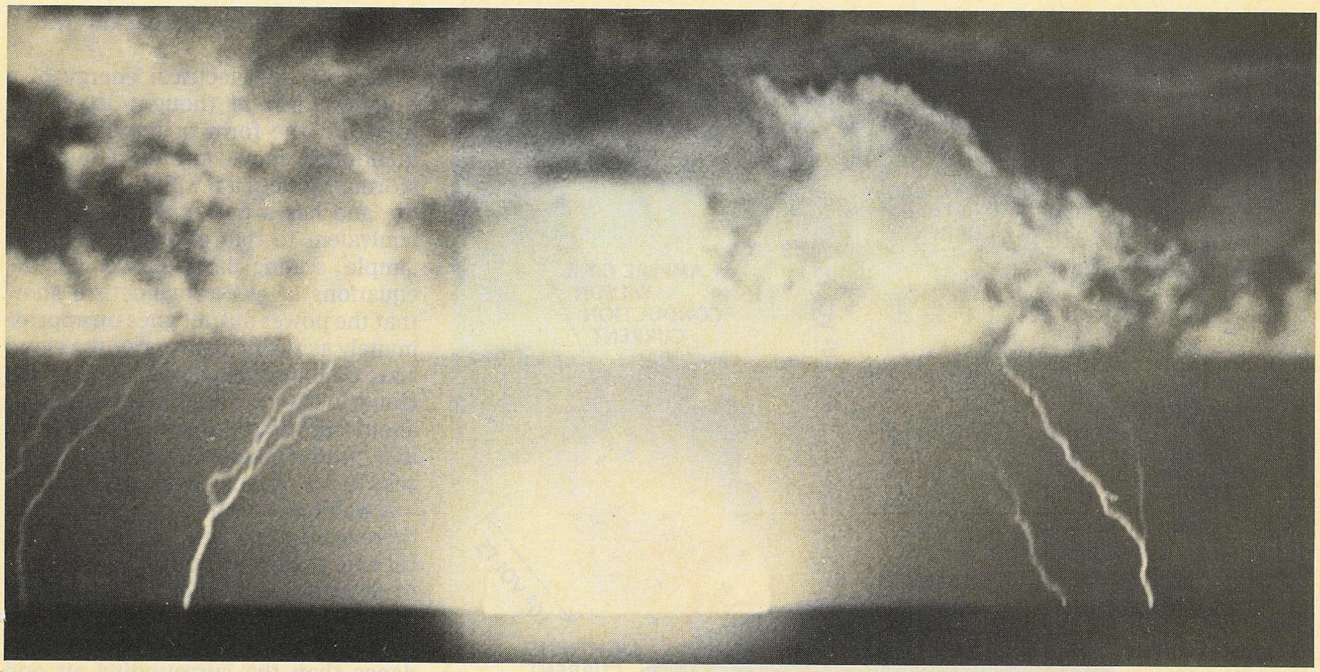
Lightning

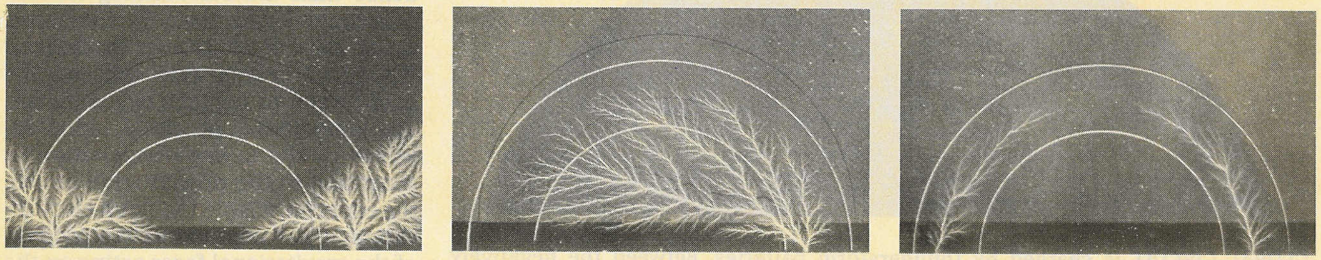
Once a thundercloud has become charged to the point where the electric field exceeds the local dielectric strength of the atmosphere—that is, the strength of the atmosphere to support a separation of electric charge—a lightning flash results. The electric field at this instant is on the order of one million volts per meter, and in less than a second the lightning bolt will transfer 10^{20} electrons' worth of charge and provide the electric power equivalent to about 100 million ordinary light bulbs. During that fraction of a second the electrostatic energy of accumulated charge is transformed into electromagnetic energy (the visible flash as well as radio interference), acoustical energy (thunder) and ultimately heat.

Almost all natural lightning is initiated within the cloud and evolves as a double-ended "tree," with one end invading negative-charge regions and the other end invading positive-charge regions. In the case of a cloud-to-ground discharge the negative end of the tree becomes a "stepped leader," which carries a negative current of a few hundred amperes downward. When the stepped leader is within roughly 100 meters of the ground, a return stroke is initiated, which transfers a 10-kiloampere current, or 10,000 coulombs of positive charge per second, upward. It is the luminous return stroke that one actually sees with the eye and so, when one speaks of cloud-to-ground lightning, one must bear in mind that the lightning travels in both directions—sometimes several dozen times [see "Thunder," by Arthur A. Few; SCIENTIFIC AMERICAN, July, 1975].

Early studies of lightning concentrated on the cloud-to-ground flashes because those were most accessible to visual and photographic observation. It turns out, however, that lightning is far more frequent and extensive within the cloud itself, where it is hidden from view because of the opacity of the cloud. More recent studies have attempted to investigate intracloud lightning with the help of radar, radio-frequency direction finders and microphones. Interest centers on the paths taken by lightning flashes and their relation to cloud structure.

Lightning is found in regions of precipitation and in regions without precipitation, within clouds and without, and its paths often appear to be very chaotic; many claims have been made that these paths are indeed random. Theoretical models for lightning paths have often focused on the role of the electric field. In other words, it was thought the strength and direction of the local electric field determined the lightning path. Until recently little attention has been paid to the role of the electric charge itself. Although the charge gives rise to the field, so that one might think knowing one is as good as knowing the other, one must also remember that an electric field can be produced locally by any number of different charge distributions. Therefore the location of the electric





IVY-MIKE TEST of a 10-megaton hydrogen bomb in 1952 generated lightning within 10 milliseconds after detonation. The intense gamma-ray burst from the explosion strips electrons from air molecules in a process called Compton scattering; the lighter electrons are rapidly moved away from the now positive air molecules, resulting in charge separation. The hemispherical symmetry of the explosion allows the charge distribution to be simulated in the laboratory. The three experiments shown at the bottom were done at the Massachusetts Institute of Technology's High Voltage Research Laboratory, where electric charge was injected into specific regions of an insulating plastic block. The models have a similar electric field near the ground but differing charge distributions. Only model 3 reproduces the IVY-MIKE lightning pattern, indicating it is the charge distribution, not the field, that predominantly determines the path of lightning. The lightning is triggered at the point on the ground where the electric field is large, and it travels upward through the region of greatest negative charge.

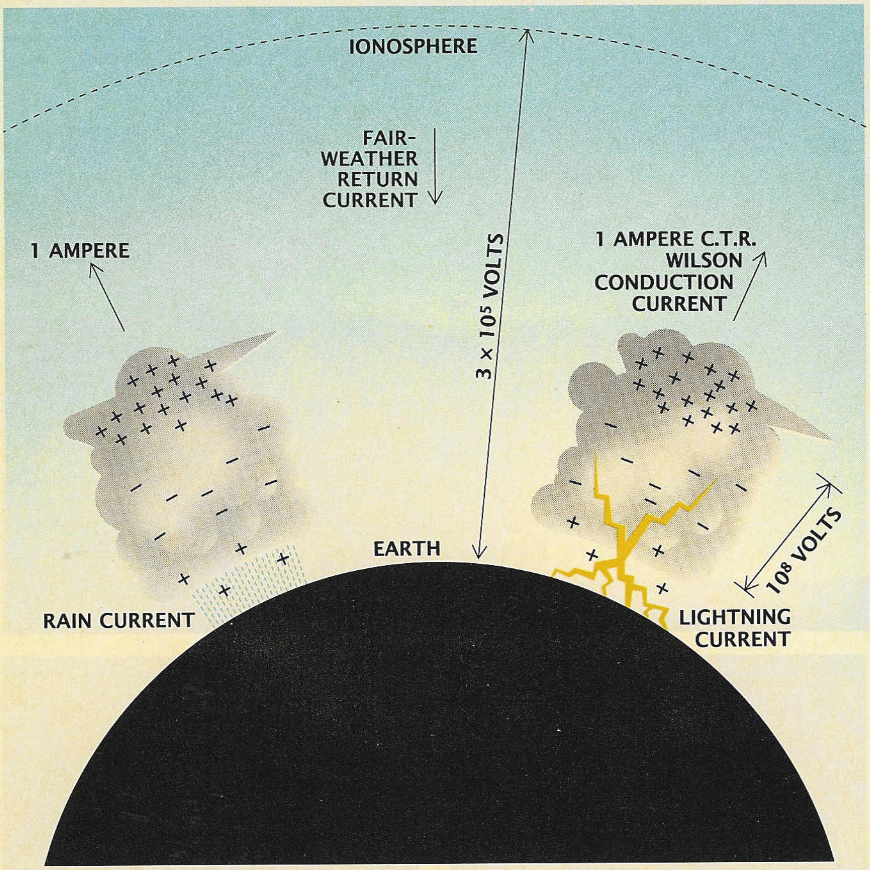
charge is a different piece of information from knowing the local field configuration. An additional complication is that the charge distribution and field are not static but dynamic; as the lightning forms and grows it will change the field dramatically, making modeling much more difficult.

Today the evidence indicates that the two ends of the lightning "tree" tend to follow paths of greatest charge concentration. For example, many observations reveal that lightning is found predominantly within the main negative-charge region.

The clearest evidence that lightning paths are governed by the distribution of charge in space, however, probably comes from studies of the behavior of lightning produced by nuclear-weapons explosions. Photographs of H-bomb tests carried out in the 1950's show that the fireball is often surrounded by lightning flashes [*see illustration on preceding page*]. In contrast to the theoretical picture of thunderclouds, here the basic charge-separation mechanism is well understood. The radial flux of high-energy photons given off by the fireball strips the surrounding air molecules of their electrons in a process called Compton scattering. The negatively charged electrons are thus concentrated in a hemispherical shell around ground zero, leaving a positively charged region in the fireball.

The hemispherical symmetry of the explosion makes it possible to construct simple theoretical and laboratory models of the charge distribution and investigate its effect on lightning paths. Chathan M. Cooke, Kenneth A. Wright and I have performed such simulations at the Massachusetts Institute of Technology's High Voltage Research Laboratory. Charge is injected in an annular pattern into blocks of highly insulating plastic that trap the charge in a manner consistent with the theoretical model. The resulting electric field is strong enough to trigger lightninglike discharges.

We find that lightning is triggered at the point near simulated ground zero where the electric field is strongest; the flash then travels upward through the region of greatest negative charge. The lightning pattern is remarkably similar to the patterns seen in the photographs of nuclear tests. Furthermore, one can construct experiments with charge distributions predicted by other theoretical models. Although some of these other models produce the same electric-field configuration at the ground, the charge distribution can be quite different. The lightning patterns do not resemble those of the nuclear tests, thereby demonstrating that it is predominantly the charge that determines the lightning path.



GLOBAL CIRCUIT is charged by thunderstorm batteries. Between the negatively charged earth and the upper atmosphere is a nearly constant potential difference of 300,000 volts. On the scale of clouds, currents of about one ampere that flow from the top of thunderstorms help to maintain the potential difference; this requires a similar current to flow from the ground to the clouds' lower regions. On the large scale, a fair-weather leakage current of about 2,000 amperes, which transfers positive charge from the upper atmosphere to the earth, would eliminate the 300-kilovolt potential difference if thunderstorms did not recharge the circuit. It is thought that thunderstorms in the Tropics, which transfer large amounts of negative charge to the ground, are the dominant agent in balancing the fair-weather current.

Energy and the Global Circuit

Most of the electrical energy of a thunderstorm is thought to be released in the form of lightning. As I mentioned above, a modest thunderstorm produces a few flashes per minute and has a power output roughly equivalent to that of a nuclear plant. Simple scaling laws based on the equations of electromagnetism show that the power output goes up approximately as the fifth power of the cloud size; doubling the dimensions of the cloud increases the power output by about thirtyfold. Large thunderstorms may produce lightning at rates in excess of 100 flashes per minute.

A well-known rule in physics is that there are no free lunches. The electrical energy released by lightning must come from somewhere. Ultimately it derives from the heat that causes water vapor to expand, to become less dense than the surrounding air and consequently to rise. As the water vapor rises it condenses or freezes; the latent heat is released and the liquid water or ice then begins to fall. The gravitational potential energy released by the falling precipitation is, according to the precipitation model, the energy available for cloud electrification; it is computed as the product of the gravitational force acting on the precipitation and the fall distance of the precipitation.

Radar measurements of falling rain and graupel particles show that in modest storms the gravitational energy is in fact much larger than the electrical energy released by lightning. For exceedingly active storms, where the electrical energy may be orders of magnitude higher, the gravitational energy and the electrical energy are estimated to be about the same. One would then expect, by conservation of energy, that at the moment of a lightning discharge, when the electrical forces suddenly decrease, the fall velocity of the precipitation should noticeably increase. Attempts have been made to measure the phenomenon by Doppler radar, which measures the velocity of a moving object, but so far the attempts have been unsuccessful. The general absence of abrupt shifts in velocity has not yet been satisfactorily explained, but small velocity changes may be masked by the turbulent motions of thunderstorms.

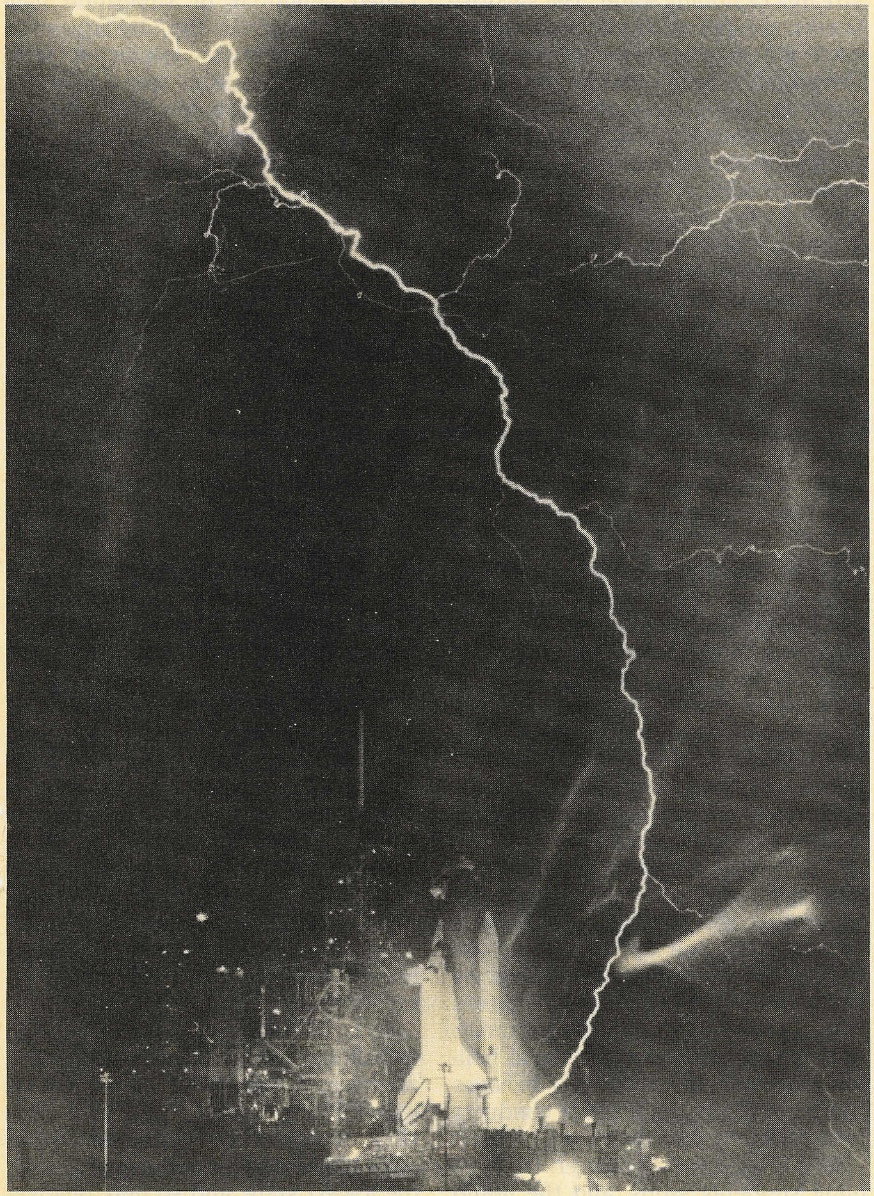
There is still another energy balance that must be maintained: that of the global electrical circuit. The earth's atmosphere is an extremely good insulator that is sandwiched between two good conductors: the earth's surface below and the upper atmosphere and ionosphere above [*see illustration on opposite page*]. These layers are the passive components of the global electrical circuit.

Between the negatively charged surface of the earth and the positively charged atmosphere is a steady potential difference of about 300,000 volts. Following the proposal originally made more than 70 years ago by Wilson, it is now generally believed this 300-kilovolt "ionospheric potential" is the result of charging by thunderstorms, which form the "batteries" of the global circuit. Electric currents of about one ampere per storm flow upward from the positive tops of thunderclouds and return to the earth in the fair-weather regions of the atmosphere.

In order for charge not to build up indefinitely in the clouds, a one-ampere current has to flow from the earth's surface to the cloud bottom. Rain currents, corona discharge and lightning all contribute to this charge transfer, but in the mid-latitudes it is not enough to balance the fair-weather return current. Where is the deficit made up? The missing batteries are found in the Tropics, where thunderstorms that are orders of magnitude larger than mid-latitude storms have flash rates large enough to charge the global circuit.

One might well ask why the earth is negatively charged in the first place. The best guess today is that the negative charge of the earth is the result of the earth's proximity to the negative end of the thunderstorm battery. The question thus reverts to why the lower part of a thundercloud is predominantly negative—and the answer to this question, once again, appears to depend on the poorly understood microphysics of ice.

In spite of the many unanswered questions, a unified picture of cloud electrification is beginning to emerge; the picture links charge separation taking place on the scale of atoms to lightning flashes that travel across distances of kilometers to an electrical circuit that spans the entire earth.



PRELAUNCH LIGHTNING at the John F. Kennedy Space Center in Florida on August 30, 1983, almost strikes the space shuttle. The storm passed and the shuttle was launched on schedule at 2:32 A.M. Approximately 44,000 thunderstorms and eight million lightning flashes take place daily around the world. In the U.S. alone lightning annually causes about 150 deaths and $20-million worth of property damage and sets 10,000 forest fires, which destroy $30-million worth of marketable timber.

FURTHER READING

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