Natural and Artificially Initiated Lightning

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Recent research on lightning has been motivated, in part, by the desire to prevent spectacular accidents, such as occurred in 1969 during the launch of Apollo 12 and in 1987 during the launch of Atlas-Centaur 67, and by the need to protect advanced ground-based and airborne systems that utilize low voltage, solid-state electronics. The present understanding of both natural and artificially initiated (triggered) lightning is reviewed, and suggestions are given for future research that can improve our understanding both of the physics of lightning and the parameters that are important for protection.

ALTHOUGH BENJAMIN FRANKLIN PROVED THAT LIGHTNING was an electrical discharge and measured the sign of the cloud charge that produced it (*1*) more than 200 years ago, modern research on the physics of lightning began in the early 20th century with the work of C. T. R. Wilson (*2*), the same scientist who received the Nobel Prize for his invention of the cloud chamber. Wilson was the first to infer the charge structure of thunderclouds and the amount of charge involved in lightning by making remote measurements of thunderstorm electric fields. In the 1930s, lightning research was motivated primarily by the need to reduce the effects of lightning on electric power systems and by the desire to understand an important meteorological process. The pace of that research was fairly steady until the 1960s when there was renewed interest because of the generally unexpected vulnerability of solid-state electronics to damage from lightning-induced voltages and currents with the resultant hazard to modern aviation systems. A good deal of the recent research has been motivated by three spectacular lightning accidents involving aircraft or spacecraft: (i) In 1963, a Boeing 707 flying at 5000 feet near Elkton, Maryland, was struck and destroyed by lightning, killing all occupants (*3*). Lightning apparently burned through one of the metal wings, or in some other manner entered the fuel tank inside that wing, and caused the fuel vapor there to explode. (ii) In 1969, Apollo 12 artificially initiated (or "triggered") two lightning flashes, one to ground and one intracloud (IC) discharge, when it was launched through a weak cold front that was not producing natural lightning (*4*). Although this rocket-initiated lightning caused major system upsets and minor permanent damage, the vehicle and its crew survived and were able to complete their mission successfully. (iii) In 1987, an unmanned Atlas-Centaur vehicle (AC/67) was launched into weather conditions that were similar to those present at the launch of Apollo 12 and triggered a lightning discharge to ground (*5*). This discharge upset the computer memory in the vehicle guidance system and produced an unplanned yaw rotation, and the associated stresses caused the vehicle to break apart.

In this article, we will survey our present knowledge about both natural and artificially initiated (triggered) lightning, and then we will suggest directions for future research that can improve our understanding both of lightning phenomena and the parameters that are needed to improve protection.

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Sources of Lightning

Most research on the electrical structure of clouds has focused on the cumulonimbus, the familiar thundercloud or thunderstorm, because this cloud type produces most lightning. There have been limited studies of the electrical properties of stratus, stratocumulus, cumulus, nimbostratus, altocumulus, altostratus, and cirrus clouds (*6*) by means of both ground-based and airborne measurements. Any of the cloud types listed above can potentially cause lightning, or some related form of electrical discharge, as can snowstorms, the clouds above volcanoes, and other turbulent environments such as dust storms.

The classic model for the charge structure of a thundercloud was developed in the 1920s and 1930s from ground-based measurements of both thundercloud electric fields and the electric field changes that are caused when lightning occurs (*2, 7*). In this model, the thundercloud forms a positive electric dipole as shown in Fig. 1; that is, a positive charge region above a negative charge region. By

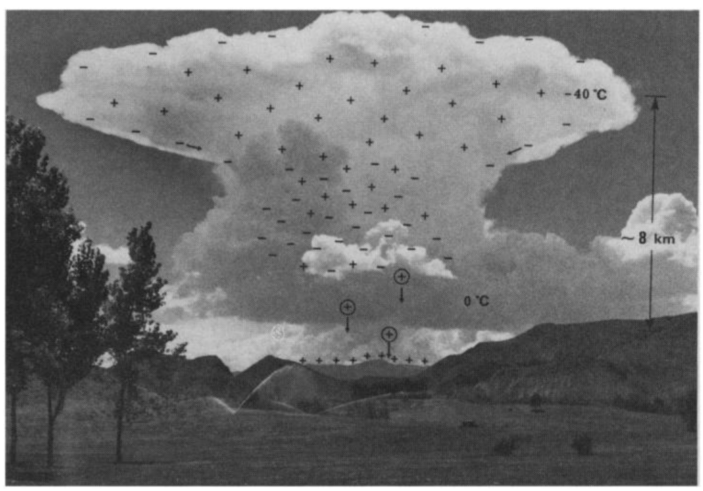

Fig. 1. Thundercloud charge distribution superimposed on a photograph of an isolated cloud in New Mexico. [Reprinted from (*16*) with permission, © 1986 National Academy Press]

the end of the 1930s, Simpson and co-workers (*8*) had verified this overall structure from measurements made with sounding balloons inside clouds and had also identified a small localized region of positive charge at the base of the cloud. Subsequent measurements of electric fields both inside and outside the cloud have confirmed the general validity of this double-dipole structure (*9, 10*). The results of a recent analysis of changes in the electric field that provide the locations and magnitudes of lightning-caused changes in the cloud charge distribution (*10*) are shown in Fig. 2. Reviews of the various processes that generate and separate charges in thunderstorms have been given by Magono (*11*), Latham (*12*), Lhermitte and Williams (*13*), Illingworth (*14*), Williams (*15*), and Krehbiel (*16*).

Natural Lightning

Lightning is a transient, high-current discharge whose path length is measured in kilometers. Well over half of all flashes occur wholly within the cloud and are called IC discharges. Cloud-to-ground (CG) lightning has been studied more extensively than other forms of lightning because of its practical importance (for instance, as the cause of injuries and death, disturbances in power and communication systems, and the ignition of forest fires) and because lightning below a cloud is more easily studied with optical techniques. Cloud-to-cloud and cloud-to-air discharges occur less frequently than either IC or CG lightning. All discharges other than CG are often combined under the general term cloud discharges.

Four different types of lightning between cloud and Earth have been identified (Fig. 3) (*17*). Negative CG flashes probably account for about 90% of the CG discharges worldwide (Fig. 3, category 1), and less than 10% of lightning discharges are initiated by a downward-moving positive leader (category 3). Ground-to-cloud discharges are initiated by leaders that move upward from the Earth (categories 2 and 4). These upward-initiated flashes are relatively rare and usually occur from mountain peaks and tall man-made structures.

Before we consider the physical properties of lightning in more detail, we will first review some recent statistics on lightning occurrence. Lightning frequencies have been studied extensively at the NASA Kennedy Space Center (KSC), Florida, because of the hazard lightning presents to ground operations and launches, and at several other locations throughout the world. Individual storms at KSC typically produced between 1 and about 4000 lightning flashes (*18*). Roughly 30 to 40% of these flashes, depending on the storm, were CG and well over half were IC. The maximum flashing rates, averaged over 5-min intervals, ranged between 0.2 and 31 discharges per minute. Over a 7-year period, the mean area density of CG flashes was estimated to be 4.6 flashes km^{-2} $month^{-1}$ with a minimum of 3.7 flashes km^{-2} $month^{-1}$ and a maximum of 21.9 flashes km^{-2} $month^{-1}$.

In the region near Tampa Bay, Florida, Peckham *et al.* (*19*) found that when storms had a CG flashing rate that increased monotonically with time to a single peak and then fell smoothly to zero, the mean storm duration was 41 min and the mean lightning area was 103 km^2. Each storm produced 73 CG flashes, on average; the mean area "density" was 0.02 flashes km^{-2} min^{-1}; the average flashing rate was 1.7 flashes min^{-1}; and the average maximum flashing rate was 3.7 min^{-1}. More complex storms that had multiple peaks in the flashing rate distribution produced, on average, mean parameters 2 to 3 times the above values with the exception of the flash density, which remained roughly constant and was generally independent of the size of the storm.

Statistics on the distances between successive CG lightning strikes

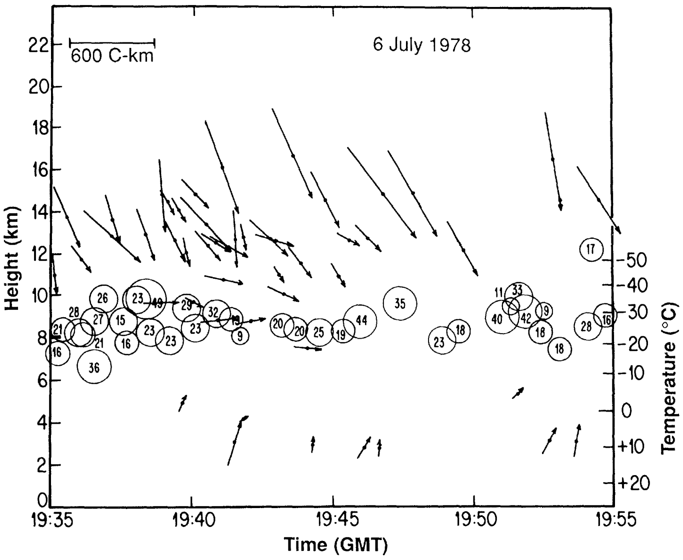

Fig. 2. Changes in the thundercloud charge distribution that are caused by CG (open circles) and IC (arrows) lightning as a function of time (*10*). Charge lowered in coulombs is shown for ground flashes and moment changes in coulombs-kilometers for intracloud discharges. The data are from a portion of an active thunderstorm at the NASA Kennedy Space Center. The open circles show the altitude and magnitude in coulombs of the negative charges removed by various (CG) lightning flashes that occurred during a 20-min period. The arrows show the changes in dipole moment in coulomb-kilometers that were produced by cloud discharges that effectively destroyed separated positive and negative charge. A downward-pointing arrow indicated positive charge was above negative charge before both were effectively neutralized. GMT, Greenwich mean time. [Reprinted from (*10*) with permission, © 1989 American Geophysical Union]

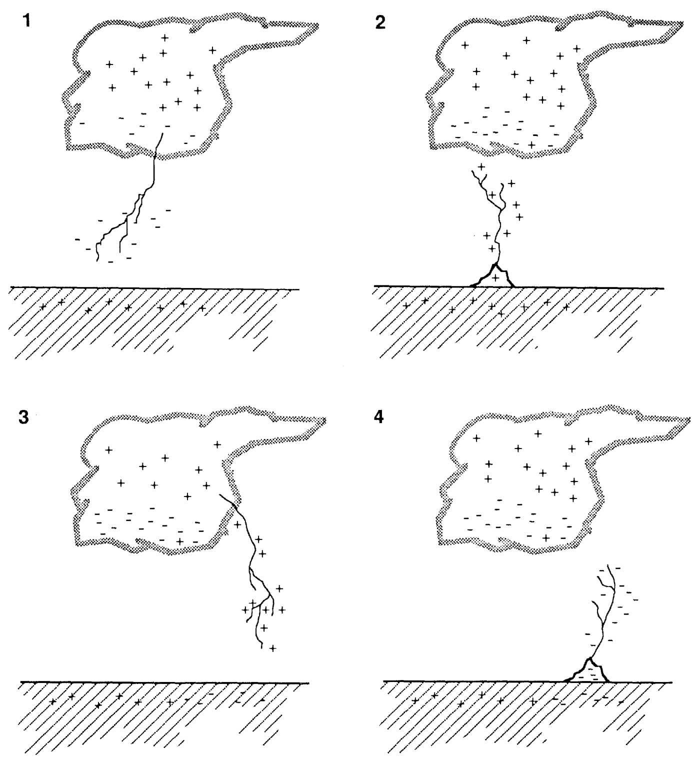

Fig. 3. Categorization of the four types of lightning between cloud and ground. Category 1 lightning begins with a negatively charged leader moving downward; category 3 discharges are initiated by a downward moving positive leader. Category 2 lightning has a positively charged leader, and hence this type effectively lowers negative charge to earth; category 4 has a negatively charged leader and effectively lowers positive charge. [Reprinted from (*21*) with permission, © 1987 Academic Press]

in Japan and Florida are found in (*20*). The CG flashes in an individual cell tend to strike within a circular area roughly 10 km in diameter, and within that area the lightning is almost random. More specifically, there is about a 20% probability that a discharge will occur either 2, 3, or 4 km from the previous one, and there is a small, but finite, probability that a discharge will be 8 km or more from the previous strike. The average value of the distance between successive strike points is about 3.5 km, and the storm-average nearest neighbor distance is about 0.5 km.

Negative CG Lightning

A photograph of a negative CG discharge (Fig. 3, category 1) is shown in Fig. 4. A flash like this begins in the cloud and effectively lowers some tens of coulombs of negative charge to Earth. The total discharge is termed a flash (as is the total discharge for other types of lightning), and flash durations are typically about half a second. A flash has several components, the most significant being three or four high-current pulses called strokes. Each stroke lasts about a millisecond, and the separation between strokes is typically several tens of milliseconds. Lightning often appears to "flicker" because the human eye can just resolve the individual pulses of luminosity that are produced by each stroke.

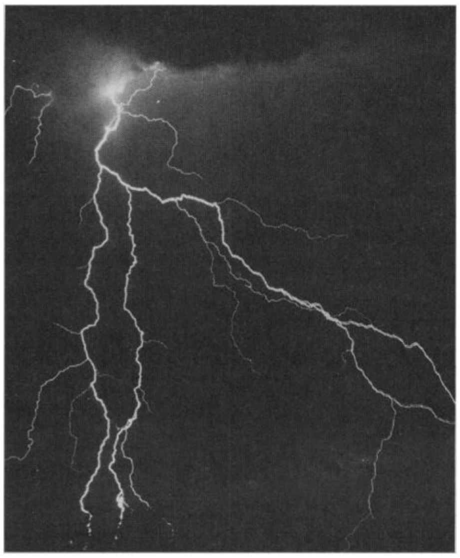

Fig. 4. A natural CG lightning flash. There are several ground strike points indicating dart-stepped leaders occurred prior to some subsequent strikes. Courtesy of George Marcek. [Reprinted from (*38*) with permission, © 1986 Dover Publications]

The sequence of luminous processes that are involved in a typical negative CG flash (*21*) is shown in Fig. 5. The stepped leader initiates the first return stroke after it propagates downward in a series of discrete steps. The stepped leader is itself initiated by a preliminary breakdown within the cloud, although there is no agreement about the exact form and location of this process. The preliminary breakdown is shown in the lower part of the cloud between the negative and lower positive charge regions in Fig. 5. High-speed photographs show that leader steps are typically 1 μs in duration, tens of meters in length, and that the pause time between steps is 20 to 50 μs. A fully developed stepped leader can effectively lower 10 C or more of negative charge toward the ground in tens of milliseconds. The average downward speed of propagation is about 2×10^5 m/s. The average leader current is between 100 and 1000 A. The leader steps have peak pulse currents of at least 1 kA. During its progression toward ground, the stepped leader produces the downward-branched geometrical structure shown in Figs. 4 and 5.

The potential difference between the lower portion of the negatively charged leader and the Earth has a magnitude in excess of 10^7 V. As the tip of the leader nears ground, the electric field at sharp objects on the ground or at irregularities on the surface increases until it exceeds the breakdown strength of air. At that time, one or more upward-moving discharges are initiated from those points, and the attachment process begins. When one of the upward-moving discharges contacts the downward-moving leader, some tens of meters above the ground, the leader is effectively connected to ground potential. The leader channel is then discharged by an ionizing wave of ground potential that propagates up the previously ionized leader channel. This process is the first return stroke. The electric field across the potential discontinuity between the return stroke, which is at ground potential, and the channel above, which is near cloud potential, is what produces the additional ionization. The upward speed of a return stroke is typically one-third to one-half the speed of light near the ground, and the speed decreases with height. The total transit time between ground and cloud is on the order of 100 μs. The first return stroke produces a peak current of typically 30 kA at the ground, with a time from zero to peak of a few microseconds. Currents measured at the ground decrease to half the peak value in about 50 μs, and currents of the order of hundreds of amperes may flow for times of a few to several hundred milliseconds. We will discuss these long-duration, low-amplitude currents later in this section.

The rapid release of return-stroke energy heats the leader channel to a peak temperature near 30,000 K and produces a high-pressure channel that expands and creates the shock waves that eventually become thunder. The return stroke effectively lowers to ground the charge originally deposited on the stepped leader channel including all the branches, as well as other cloud charge that may become available at the top of the channel.

When the return-stroke current ceases, the flash, including various discharge processes within the cloud, may end. In that case, the lightning is called a single-stroke flash. On the other hand, if additional cloud charge is available, a continuous dart leader can propagate down the residual first-stroke channel and initiate another return stroke. During the time between the end of the first return stroke and the initiation of a dart leader, so-called J- and K-processes occur in the cloud. The dart leader has a peak current of 1 kA or more and lowers a total charge on the order of 1 C at a speed of about 3×10^6 m/s. Some dart leaders become stepped leaders toward the end of their progression toward ground and do not follow the previous return stroke channel. The flash in Fig. 4 apparently had two or possibly more of these dart-stepped leaders. Dart leaders and return strokes subsequent to the first are usually not branched.

The time between successive strokes in a flash is usually several tens of milliseconds, but can be tenths of a second if a continuing current persists in the channel after a return stroke. Continuing currents are of the order of 100 A and represent a direct transfer of charge from cloud to ground (*22*). Between 25 and 50% of all CG flashes contain a continuing current component (*18, 22*).

As a way of summarizing the above processes and illustrating the type of lightning data that can be obtained with photographic techniques, Fig. 6 shows a hypothetical streak photograph and a corresponding still photograph of a three-stroke lightning flash.

A comprehensive list of lightning current parameters have been derived from tower measurements in Switzerland during strikes initiated by downward leaders (*23*). In these tower studies the maximum rate-of-rise of current (*di/dt*) and the duration of the current front, important parameters for determining lightning-induced voltages in systems, are limited by the bandwidth of the measuring apparatus. More adequate values for these parameters are given in the final section of this article.

Positive CG Lightning

Positive flashes to ground (category 3 in Fig. 3) are of considerable practical interest because their peak currents and total positive charge transfer to ground can be much larger than the more common negative flashes (*17, 23, 24*). The largest peak currents that have been recorded, those in the 200- to 300-kA range, were produced by positive return strokes (*23*). Positive flashes to ground are initiated by leaders that do not exhibit as distinct steps as their negative counterparts. Rather, they exhibit a more or less continuous luminosity that is modulated in intensity. Positive flashes usually contain only a single return stroke followed by a period of continuing current (*25*). Positive flashes are probably initiated by the upper positive charge in thunderclouds (Figs. 1 and 5) where this charge has been separated horizontally from the lower negative charge by

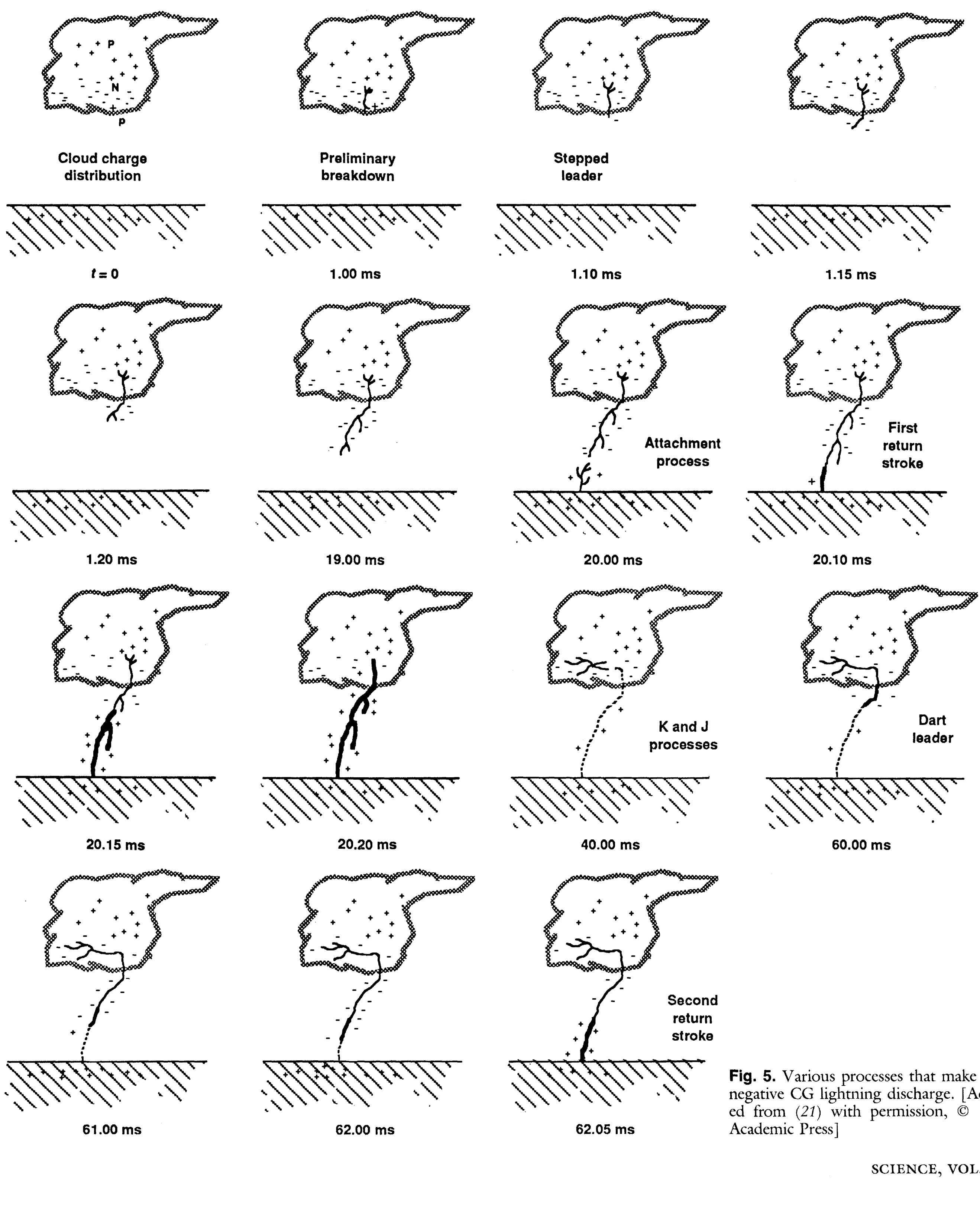

Fig. 5. Various processes that make up a negative CG lightning discharge. [Adapted from (*21*) with permission, © 1987 Academic Press]

wind shear (*24, 26*), but this may not always be a necessary condition (*27*).

Positive flashes are the majority of flashes to ground in winter thunderstorms (and snowstorms) even though these storms produce few flashes overall; and they are relatively rare in summer thunderstorms, only 1 to 15% of the flashes (*28*), although storms with predominantly negative lightning often end with positive discharges. The fraction of positive discharges in summer thunderstorms apparently increases with increasing geographic latitude and with increasing height of the local terrain; that is, the closer the cloud charge is to the ground, the more probable is positive lightning, but, again, not enough is known about positive lightning to be able to say that this is always a necessary condition.

Upward Lightning

Lightning is sometimes initiated by upward-moving leaders that rise from tall mountain peaks or man-made structures, as indicated by categories 2 and 4 of Fig. 3. A photograph of upward lightning from four television towers is found in Fig. 7. Upward-moving leaders can be initiated artificially (triggered) when a grounded conductor of the order of 100 m in length is rapidly carried upward by a rocket below a charged cloud (Fig. 8).

The leaders in upward-initiated lightning are usually positive (Fig. 3, category 2). Positive upward leaders show a continuous luminosity that is modulated in a fashion similar to positive downward-stepped leaders. Negative upward leaders (category 4) exhibit a stepped behavior that is similar to negative downward-stepped leaders. Category 4, as noted earlier, is the rarest form of lightning between cloud and ground.

Positive upward leaders often enter the cloud and produce only a more or less continuous flow of current, of the order of 100 to 1000 A, at ground. In about half of the upward-initiated events, however, the continuous current is followed by a sequence of dart leaders and return strokes that are similar to those following first strokes in natural CG discharges that are initiated by negative downward-moving leaders. A detailed review of the measurements that have been made on upward-initiated lightning is found in (*21*).

Cloud Discharges

We have previously defined a cloud discharge to be any lightning that does not connect to ground. As stated earlier, the majority of all discharges occur within the cloud. Cloud discharges can be subdivided into IC, intercloud, and cloud-to-air flashes, but there are no experimental data at present to distinguish between these three types. Indeed, on the basis of electric field records, there is considerable similarity between these discharges (*29*). The term cloud discharge could also be applied to those portions of a flash to ground that take place within the cloud. In some cases, flashes that are primarily within the cloud, and are best characterized as cloud flashes, produce a channel to ground, seemingly as an unimportant by-product.

Intracloud flashes typically occur between positive and negative charge regions or represent discharges away from concentrated regions of positive or negative charge and have total durations that are nearly the same as ground flashes, about half a second. A typical cloud discharge effectively moves tens of coulombs of charge over a distance of 5 to 10 km. The discharge process is thought to consist of a continuously propagating leader that generates weak return strokes called recoil streamers when the leader contacts pockets of space charge opposite to its own. The electric field changes that are associated with recoil streamers are termed K-changes. K-changes are though to be similar, but usually of opposite polarity, to the K-changes that occur in the intervals between return strokes in CG discharges. A detailed review of the literature on cloud discharges is found in (*21*).

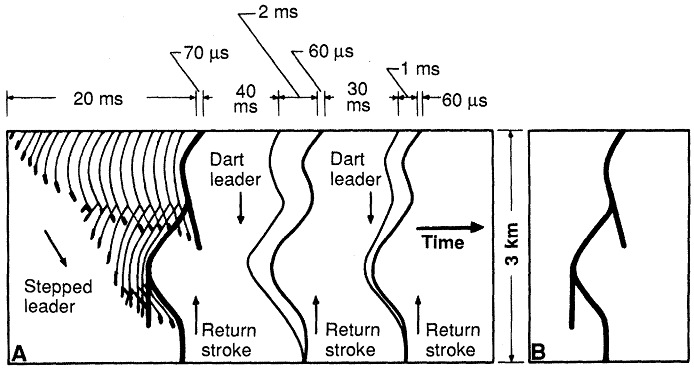

Fig. 6. (**A**) Luminous features of a lightning flash below cloud base as would be recorded by a streak camera. Increasing time is to the right. For clarity the time scale has been distorted. (**B**) The same lightning flash as would be recorded by a camera with stationary film. [Adapted from (*21*) with permission, © 1987 Academic Press]

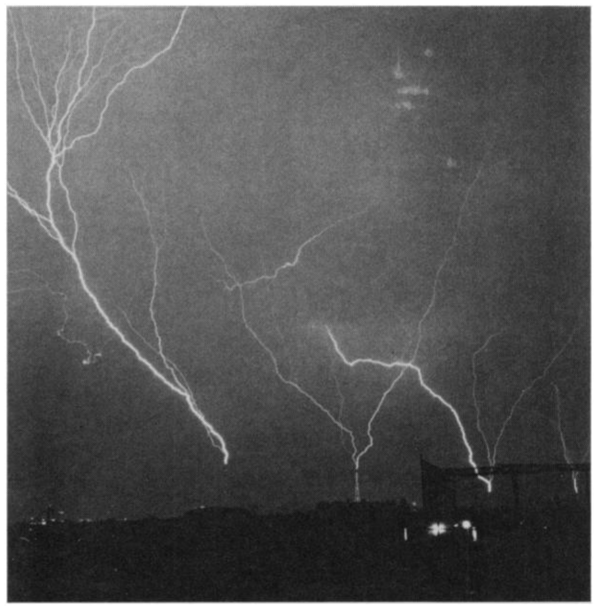

Fig. 7. Four upward lightning flashes initiated concurrently, by visual observation, from four 300-m tall televison transmission towers during a frontal thunderstorm in Kansas City. The TV towers are located along a line 10 km long. Courtesy of C. G. Kitterman. [Reprinted from (*21*) with permission, © 1987 Academic Press]

Top-of-the-Cloud and Clear Air Lightning

There are occasional reports of lightning propagating upward from the tops of clouds and perhaps to the ionosphere (*30*). Lightning has also been reported when there is a clear blue sky (*31, 32*), commonly referred to as a "bolt from the blue." Most of these reports, however, refer to a situation where there is blue sky overhead and the thunderstorm is 10 or more kilometers away, out of viewing range, from where the lightning originates. However, there are photographs and supporting charge locations that show that a triggered discharge can occur entirely in clear air near a thunderstorm (*32*). In the case cited, there was a thunderstorm

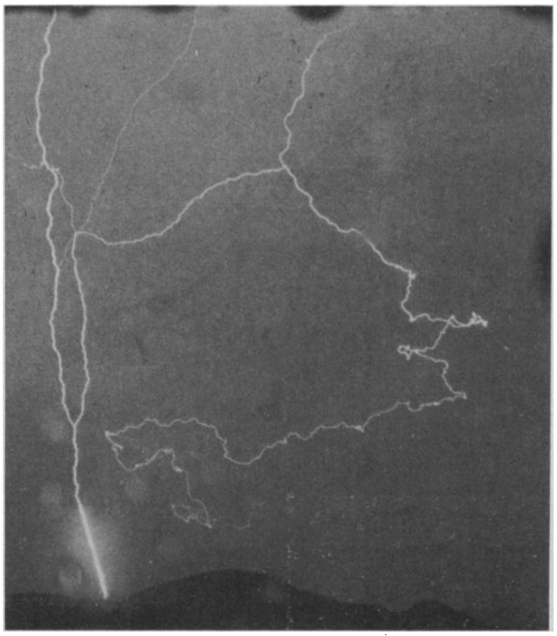

Fig. 8. Rocket initiated lightning. The straight part of the channel at the bottom is caused by the wire between the rocket and ground. Courtesy of P. Hubert. [Reprinted from (*21*) with permission, © 1987 Academic Press]

about 10 km away, and the lightning was artificially initiated by firing a small rocket upward that trailed a grounded wire. There were high electric fields, but the sky overhead where the charge appears to have been located was mostly clear with broken altocumulus and altostratus clouds at higher altitudes.

Artificially Initiated (Triggered) Lightning

We can define triggered lightning as discharges that occur because of the presence of man-made structures or events. Such lightning is characterized by an initial upward-moving positive leader if it is triggered below a negative charge region of the cloud, as is usually the case for small rockets trailing grounded wires. Discharges initiated by upward-moving leaders also occur naturally, for example, from mountain tops; triggered lightning that occurs via an upward leader is expected to be similar to natural upward events. Upward-initiated lightning has no "first return stroke" of the type that is always observed in normal CG lightning that is initiated by a downward leader. Rather, the initial part of the discharge is taken by an upward-moving leader and any continuous current that may follow when that leader reaches the cloud. This upward process is sometimes followed by combinations of downward-moving dart leaders and upward-moving return strokes that appear to be very similar to subsequent strokes in normal CG flashes. The physical processes that occur in discharges that are initiated artificially within the cloud or relatively far above ground by aircraft or space vehicles and are not attached to ground are not as well understood as are discharges initiated by objects below the cloud that attach to ground.

In general, lightning can be initiated artificially by rapidly introducing a long electrical conductor into a region of relatively high electric field. In this case, the conductor will enhance the existing field to a value sufficient to cause electrical breakdown. Brook *et al.* (*33*) found that small balloons flown continuously on metal wires of several kilometers in length did not get struck, even during periods of active lightning. Further, they showed that in the laboratory, artificial initiation of a spark would occur only with the rapid introduction of a conductor into an electric field, and that the steady presence of that conductor did not produce a spark discharge. Brook *et al.* suggested that corona discharges act to shield a stationary conductor so that the high fields necessary to initiate lightning are not obtained, whereas the field enhancement during a rapid introduction of a conductor is not reduced significantly by corona since there is not a sufficient time for its production.

Newman *et al.* (*34*) first demonstrated that lightning can be artificially initiated or triggered by launching small rockets trailing wires that were grounded to a ship at sea. Lightning can also be initiated artificially over land in a similar manner, and extensive measurements have been made on such discharges (*35–37*). In a related, but accidental, example of artificial initiation, a plume of water from a depth charge explosion in the Chesapeake Bay initiated a three-stroke lightning flash (*33, 38*).

Examples of lightning being initiated by long, conducting objects not connected to Earth are provided by the strikes to Apollo 12 (*4*); by the strike to the Atlas-Centaur 67 (*5*); by lightning triggered by small rockets trailing 100 to 200 m of ungrounded conducting wire, the lower portions of which were 50 to 150 m above the ground at initiation (*36*); by accounts of lightning strikes to aircraft flying in clouds that were otherwise not producing lightning (*39*); and by radar measurements of the formation of lightning-produced echoes at a research F-106 aircraft and their propagation away from the aircraft (*40, 41*).

A photograph of lightning that was triggered by a small rocket trailing a ground wire is given in Fig. 8. Basically, the rocket is fired upward at a velocity near 200 m/s and a grounded wire is unspooled either from Earth or from the rocket. The upward leader is initiated from the tip of the rocket when the rocket is at an altitude of typically 200 to 300 m. A good probability of triggering lightning is assured if the launch is made when the static field at the ground is between 5 and 10 kV/m, but triggering can occur when the field at ground is only about 1 kV/m (*42*).

In New Mexico, the following relation was found between the rocket height H in meters at initiation and the field E in kilovolts per meter at ground level just before rocket launch (*36*)

$$H = 3900\ E^{-1.33}\ \mathrm{m} \qquad (1)$$

In general, the larger the value of the field at ground, the lower the height of the rocket at the time the upward leader is initiated. The average rocket heights and static field values at the time of initiation are summarized in Table 1. Apparently it is the enhanced value of the electric field at the rocket tip that is the most significant parameter in determining the triggering probability.

It is now thought that most lightning strikes to aircraft in flight are triggered by the aircraft, as opposed to the aircraft's intercepting a naturally occurring flash (*41*). Arguments that support the initiation of lightning by aircraft have, until recently, been made primarily on the basis of observations of strikes to airplanes in clouds that had not previously produced natural lightning (*39*). Recent analyses of ultrahigh frequency (UHF) radar echoes during lightning strikes to a F-106B research aircraft have provided the first direct evidence of triggering (*40*). It was determined that the majority of lightning echoes were initiated by the F-106B, at least within the accuracy of the radar resolution. Visual and television records of the channel development on the F-106B were consistent with that view (*41*).

A model for lightning initiation called the "bi-directional" or "uncharged leader" theory (*41, 43*) may well be applicable to lightning initiation by aircraft and other airborne vehicles. The bi-directional leader starts where the electric field is high and propagates in both directions away from that region. The total charge on the leader is approximately zero. The aircraft is an electrical conductor and produces a region of high electric field by distorting and enhancing the ambient electric field in the environment. The shape and size of the aircraft are the most important factors in determining the enhancement factor. Normally, the field will be highest at the nose, wingtips, or vertical stabilizer. When the field is enhanced to the point of electrical breakdown, roughly 2 MV/m at altitude, the aircraft can trigger lightning if a number of other factors, such as the spatial extent and energy content of the environmental field are favorable. The key point is that triggering is possible under many environmental conditions where natural lightning will not occur. This is supported by many records of aircraft strikes in nonstormy clouds (*44*); and the observation that aircraft often become involved with lightning when natural icing conditions are sought during certification tests (*45*).

Recommendations for Future Research

When one is faced with the possibility of a lightning hazard, there are two methods of protection: (i) identify and avoid the hazard; and (ii) protect and harden the system of interest to withstand the effects of nearby and direct strikes.

In the last 10 years, exceptional progress has been made in the technology for identifying and locating natural CG lightning, and nationwide networks of lightning sensors with a wideband magnetic direction-finding technology (*46*) that produce lightning locations in real time are now operational in the United States (*47*), France (*48*), Japan (*49*), and Sweden (*50*). Similar networks are presently being assembled throughout the world (for example, Spain, Taiwan, Korea, Australia). All networks are or will be used both for research and for providing warnings of natural lightning in a variety of applications. An example of a lightning map produced by the U.S. National Lightning Detection Network operated by the State University of New York at Albany (SUNYA) is given in Fig. 9. The expansion of these lightning detection networks and warning systems should be continued.

In the case of triggered lightning, the primary atmospheric electrical hazard to aircraft and space vehicles, much research needs to be done on the meteorological and electrical environments that present a threat and on the forecasting of these conditions. Again, since triggered lightning can occur within and near clouds that are not producing natural lightning, triggered discharges are often unexpected.

Most research to date on the electrical structure of clouds has focused on the thunderstorm. A variety of other clouds can also be electrified, but we still do not know the best ways to identify these clouds or, in fact, what electrical environments present a triggered lightning hazard. Now there is a new urgency to understand better the processes that produce electric fields in all types of clouds and to understand how these fields initiate a discharge. We also need to understand the other factors that contribute to a triggered-lightning hazard.

In order to design better lightning protection systems to improve the capability of aircraft and space vehicles to withstand the effects of nearby or direct strikes, it is essential to understand the nature of the lightning environment near and at the point of a direct strike. Among the most important parameters responsible for coupling lightning signals to electronic systems is the maximum of di/dt, the rate of change of current with respect to time. Recent return stroke current measurements on towers with wideband transient recorders (*51*), currents measured during lightning strikes to a F-106B research aircraft (*52*), and return stroke current measurements in rocket-initiated discharges (*53*) show that the peak di/dt is considerably larger than was believed to be the case just 10 years ago. A maximum di/dt of 3.8×10^{11} A/s has been measured on the F-106 B aircraft in flight, and values above 2×10^{11} A/s occurred frequently (*52*). Only a few measurements of di/dt have been made with sufficient bandwidth on natural return strokes, but from this small sample a peak value of 1.8×10^{11} A/s has been observed (*51*). Finally, the rocket-triggered discharges to saltwater at the NASA KSC have produced a peak di/dt for return strokes of 4.1×10^{11} A/s (*53*). Thus, from the limited data that are available, we expect that a peak di/dt near 5×10^{11} A/s is possible, even at flight altitudes.

The electric and magnetic fields that are produced by natural return strokes also suggest that the stroke currents have values of di/dt approaching 10^{12} A/s. Measurements of the electromagnetic fields produced by strikes to saltwater, under conditions where the propagation between the flash and the recording instrumentation did not introduce distortions, have yielded a mean 10 to 90% field rise time of 90 ns in the "fast transition" during the initial rise to peak (*54*). Fields measured during very near strikes in New Mexico (*55*) exhibit rise times that are consistent with those of Weidman *et al.* (*54*). The current rise times that are inferred from the measured field rise times depend on the return stroke current model, but nevertheless the values are likely to be equal to or within a factor of 2 of the field rise time (*54, 56*). If, for example, a return stroke causes a "fast transition" rise time of about 0.1 μs, the inferred current

Table 1. Mean rocket height (H) and mean static electric field (E) at upward-leader initiation [adapted from (*21, 42*)].

Location	H (m)	E (kV/m)
Hokuriku area of Japan	142*	7.4*
St. Privat d'Allier, France	210	10†
Langmuir Laboratory, near Socorro, New Mexico	216	8.8†‡
Near Melbourne, Florida	380	6.3†
Kennedy Space Center, Florida	310§	5.0†§

*Median given instead of mean. †Negative lightning only. ‡Calculated from Eq. 1. §Measurements from 1983 to 1987 (*58*).

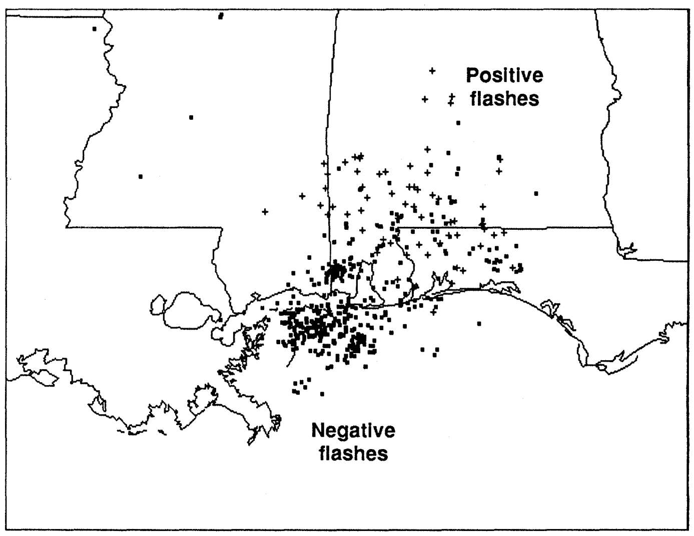

Fig. 9. A lightning map from the U.S. National Lightning Detection Network operated by SUNYA (*47*). Lightning ground strike locations along the coast of the Gulf of Mexico are shown for the period 13:30 to 14:30 GMT on 22 February 1987. Small squares indicate flashes lowering negative charge to ground; pluses indicate flashes lowering positive charge to ground. The storm system produced spatially separated positive and negative ground flashes a phenomena first reported and referred to as a "bipole pattern" by SUNYA researchers (*47*) and now recognized as a fairly common occurrence. [Reprinted from (*47*) with permission, © 1987 American Geophysical Union]

derivative for a current of 10^5A is on the order of 10^{12} A/s. There is some evidence that field rise times are roughly the same for both small and for large return stroke currents; hence, larger currents will tend to have larger values of *di/dt*. This result is supported by the results of triggered lightning experiments (*53*) that show a correlation between peak stroke currents and the maximum values of *di/dt*. The relatively high values of *di/dt* obtained by direct and indirect methods are to be compared with the present test standards for the worst-case lightning, 1 to 2×10^{11} A/s (*57*).

Besides accurate values of *di/dt*, some of the more important aspects of lightning vis-a-vis lightning protection that we also need to understand better are: the total wave shapes of the currents that are associated with all of the salient lightning processes in both natural and triggered events, the physical processes by which natural lightning attaches to ground-based structures and to aircraft, and the role of the structures and aircraft in initiating lightning.

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